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Preface

The papers in this volume were the fruitful scientific results of the Second International Conference on Social Robotics (ICSR), held during November 23–24, 2010 in Singapore, which was jointly organized by the Social Robotics Laboratory (SRL), Interactive Digital Media Institute (IDMI), the National University of Singapore and Human Language Technology Department, the Institute for Infocomm Research (I²R), A*STAR, Singapore.

These papers address a range of topics in social robotics and its applications. We received paper submissions from America, Asia, and Europe. All the papers were reviewed by at least three referees from the 32-member Program Committee who were assembled from the global community of social robotics researchers. This volume contains the 42 papers that were selected to report on the latest developments and studies of social robotics in the areas of human—robot interaction; affective and cognitive sciences for interactive robots; design philosophies and software architectures for robots; learning, adaptation and evolution of robotic intelligence; and mechatronics and intelligent control.

We would like to express our sincere gratitude to the members of the International Advisory Board, Organizing Committee and the Program Committee for their hard work. We thank Norbert Jesse (TU Dortmund) and Cheng Xiang (NUS) for their crucial advice regarding the publication and to Alfred Hofmann of Springer Heidelberg for welcoming this volume. We are very grateful to the keynote speakers Jun-Ho Oh (KAIST) and Tianmiao Wang (BUAA) for giving a holistic view of how the social robotics field is evolving and how it will impact our lives in the future. Finally, we thank all the authors, referees, student helpers and the various sponsors for their valuable contributions toward the success of this conference.

Shuzhi Sam Ge
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ICSR 2010 was organized by the National University of Singapore, and Institute for Infocomm Research.

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A Multimodal Human-Robot-Dialog Applying Emotional Feedbacks^{*}

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Abstract. This paper presents a system for human-robot communication situated in an ambient assisted living scenario, where the robot performs an order-and-serve-procedure. The interaction is based on different modalities that extract information from the auditory and the visual channel in order to obtain an intuitive and natural dialog. The required interaction dialog structure is represented in the first-order logic, which allows to split a complex task into simpler subtasks. The different communication modalities are utilized to conclude these subtasks by determining information about the human interaction partner. The system works in real-time and robust and utilizes emotional feedback to enrich the communication process.

1 Introduction

Despite of many advantages of computers (data storage and quick data processing), human-computer interaction still lacks a natural way of communication and further human-interaction techniques like gestures and mimics. Traditional human-machine interaction relies on a fixed set of operations performable on the machine in a certain way. These operations are static and force the human to adapt to the machine interface.

Instead, we aim at granting machines the ability to adapt to typical human behavior [1]. The idea is to equip machines with higher flexibility in the interaction process. To accomplish this objective, the different steps of interaction have to be performed autonomously and robustly and machines need to infer information from typical human interaction channels, such as gaze, facial expressions, head gestures or speech.

We tackle this challenge in a two-fold approach. Firstly, we present an abstraction of human-machine dialogs by using first order logic. By applying equivalence rules,

^{*} All authors contributed equally.

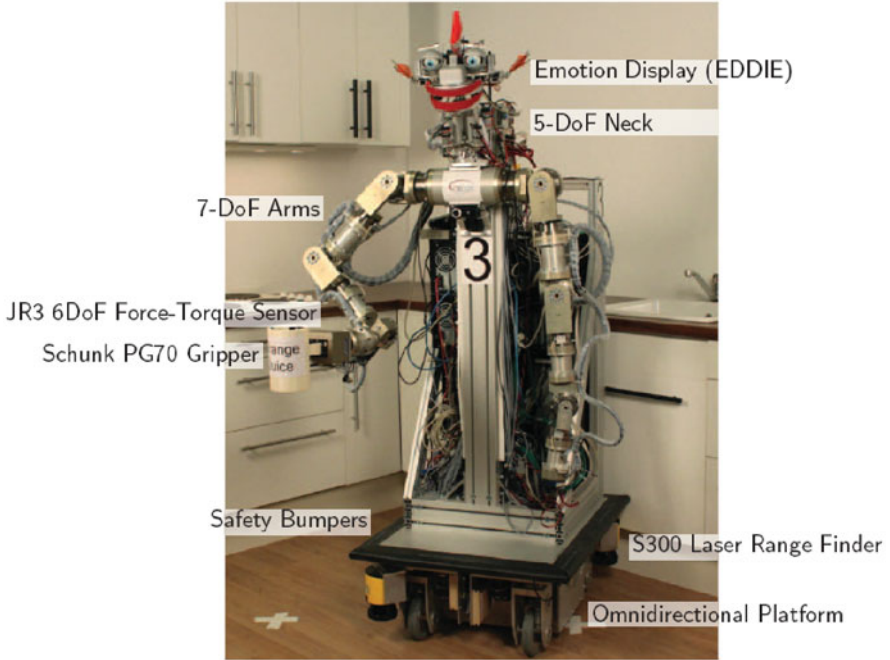


Fig. 1. Robot hardware overview

missing information is determined and complex tasks can be split into subtasks. This allows for an intuitive representation of dialogs as well as high flexibility during runtime. Secondly, we integrate multiple modalities, like emotional feedback, in the dialog to better approximate the natural human communication with a robot (see Figure 1).

1.1 Related Work

In conversational systems, Spoken Language Understanding (SLU) aims at extracting speech concepts from spontaneous speech and their relations. With increased complexity in spoken dialog systems, a richer set of features is needed to perform SLU, ranging from a-priori knowledge over long dependency dialog history to system belief [2].

A rough separation of systems for multimodal fusion leads into two classes: early fusion systems and late fusion systems [3]. Systems that integrate several modalities already on feature level are called early fusion systems. This approach is very popular for systems that integrate modalities like speech and pen input, which are closely correlated to each other. In [4] an extensive overview of several early fusion systems is given.

In recent years, late fusion systems have become more popular. For each modality, those systems involve separate recognition modules, which send their recognition

results to a multimodal fusion component. This component generates a combined interpretation of the input. Examples for late fusion systems are the robot systems presented in [5] and [6]. The integration of vision and speech enables both of these robots to communicate with humans.

We apply Hidden Markov Models (HMMs) [7] to the recognition of head gestures as well as to person identification. HMMs represent a sequence of feature vectors using statistical processes. They have been proven highly applicable to both, forming an abstraction of sequential processes and determining the probability that a specific feature vector sequence is generated by a modeled process.

Referring to the survey of Pantic et al. [8], the computational task of facial expression recognition is usually subdivided into three subordinate challenges: face detection, feature extraction, and facial expression classification. After the position and shape of the face in the image are detected in the first step, descriptive features are extracted in the second step. In the third step, high-level information from these features is derived by a classifier. Due to the generality of this approach, we apply it to recognize head gestures and person identification.

Models rely on a priori knowledge to represent the image content via a small number of model parameters. This representation of the image content facilitates and accelerates the subsequent interpretation task. Cootes et al. [9] introduce modeling shapes with Active Contours which use a statistics-based approach to represent human faces. Further enhancements extended the idea and provided shape models with texture information [10]. However, both models rely on the structure of the face image rather than the structure of the real-world face. Therefore, information such as position or orientation in 3D space is not explicitly considered but has to be calculated from the model parameters. Since this mapping is again not provided by the model, it is error-prone and renders them difficult for extracting such information.

Recent research considers modeling faces in 3D space [11][12]. In contrast to 2D models these models directly provide information about position and orientation of the face.

Face recognition is an important topic for security relevant systems. In early 1990 a revolutionary face recognition algorithm was developed by Turk and Pentland, called Eigenfaces [13]. When HMMs are applied for classification, typically we use continuous HMMs with one Gaussian per state, due to the large number of states and the limited training data for each face. However it turned out that discrete modeling techniques in conjunction with HMMs are efficient for large vocabulary speech recognition (LVCSR) and even in the field of handwriting applications [14][15]. Thus, it seems promising to test this technology also for our face recognizer. The advantage of discrete systems is the higher computation speed and smaller model size compared to continuous HMMs.

1.2 Organization of the Paper

The remainder of this paper is structured as follows: In the subsequent Section, a short overview of the scenario is given. Section 3 gives a general system overview and focuses on the following topics: *Dialog Manager* (3.1), *Communication Backbone* (3.2), *Person Identification* (3.3), *Head Gestures* (3.4) and *Robotic Head* (3.5).

The paper presents a conclusion and closes with an outlook over future work in Section 4.

2 Scenario Description

Our scenario is located in an ambient assisted living environment where the robot takes the role of a waiter. In general, the ordering dialog is initiated when a new guest is entering the scene. Afterwards the robot approaches the human by utilizing sophisticated navigation and path planning strategies combined with online collision avoidance and orients itself towards the guest, providing a comfortable communication situation. After the adjustment of the "eyes" of the robotic head, the face based verification is conducted (for more information see Section 3.3). If the person is known, the guest is approached directly with his name, otherwise a more formal kind of greeting is applied. The robot takes the first initiative by asking the dialog partner what kind of drink is desired. The human customer can ask for different drinks ranging from coffee to water. The order is conducted via speech and can be confirmed by the user either by speech or head gestures (nodding or shaking). Based on positive or negative dialog feedback, the emotions of the robotic head are set correspondingly. For example, if the speech recognition module fails to recognize a name of a drink, the robot informs the user of this failure, which is done both verbally and non-verbally by the speech output and the facial expression of sadness.

Additionally, to signal the readiness for speech input, the head can arrange the "ears" showing a listening behavior. As soon as the ordering process is accomplished, the robot starts to fetch the corresponding drink from a bartender and returns the drink to the customer. With a handover the cup is delivered to the thirsty guest. In the ordering dialog the robot can choose from a large set of possible phrases (english or german), where for each step in the ordering dialog, several sets of phrases are available, e.g. the greeting sequence can start with "Hello.", "Hi.", "How are you?" etc. For gaining a more natural and intuitive dialog, the robotic head is also equipped with so called "idle motions" to simulate a vivid behavior.

3 System Overview

We equipped a robot with visual and auditory interaction capabilities. The complete platform is mobile and therefore able to move in the laboratory. An in-eye camera system infers visual information about the human interactant to identify the person from its face and recognize head gesture. A mounted robot head signals the robot state back to the human via the display of facial expressions. In addition, a system of microphones and speakers is utilized to communicate with the human via natural language. Therefore, our system provides a bidirectional communication based on the visual and auditory channel.

3.1 Dialog Manager

A dialog manager keeps track of the ongoing communication to estimate when human user or machine response is expected by the dialog partners. The complete dialog

structure is represented by first-order logic. Tasks to solve are represented by predicates with variables. These variables represent information which is to be determined during the dialog. Equivalence rules on these predicates are specified to navigate through the dialog by splitting a task into several subtasks. Evaluating predicate truth values and binding variables models real-world interaction.

We demonstrate this with help of an example that consists of the task of serving a human a drink. This task is represented by the predicate $orderDialog(A,B)$ with A being the person to be served and B being the drink. The dialog manager inspects the equivalences of the system and applies a rule replacing the $orderDialog(A,B)$ predicate with $isIdentified(A) \ \& \ isOrdered(B) \ \& \ isConfirmed(B)$. In the next step, the dialog manager will determine the truth value $isIdentified(A)$ by inspecting the value of A . At this point, interaction with the environment is required to determine what person is interacting with the robot, setting the value of A . At the same time, the predicate $isIdentified(A)$ evaluates to `true`.

In a similar manner, $isOrdered(B)$ is evaluated by assigning some name of a drink from the speech recognition system to the variable B . In the last step, the value of $isConfirmed(B)$ is determined from either speech recognition or head gesture recognition.

Note that this representation allows to integrate different sensory modules that determine information about the environment. The information determined by the modules is considered in a very similar manner in the dialog structure, simplifying the integration of multiple modalities.

We will now introduce the modules considered in the example dialog (see Figure 2).

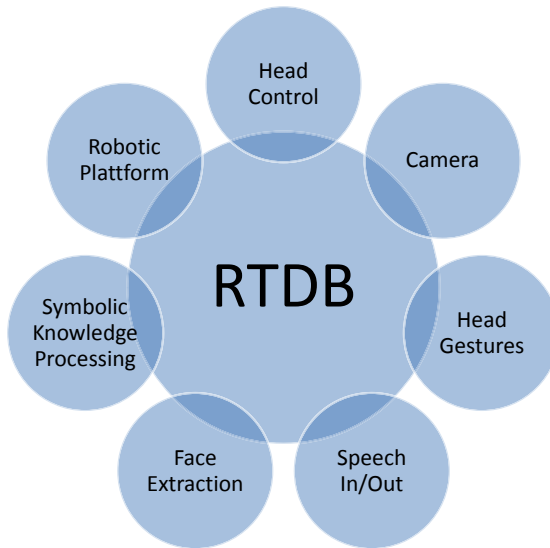


Fig. 2. Schematic System Overview

3.2 Communication Backbone

For the described setup and the desired functionalities of the system, a lot of modules are required, orchestrated with a suitable communication backbone basing on the Real-time Database (RTDB) introduced in [16]. The RTDB is based on data-objects, which are written by input modules (called writers) to be accessible by multiple processing modules (called readers) without blocking effects, exploiting a shared memory characteristic. For example, a camera image can be stored in the object buffer allowing all image processing modules to analyze this image in parallel. In the following we will present a short overview of the involved software modules basing on the RTDB. These software modules can be roughly subdivided into two entities:

Module Controlling. A generic control container is supplied by every processing module for delivering an inter-process communication. Other modules can write commands into a container and will receive in turn a result object containing information about the processed command. This can be used for basic commands like "stop" or "start processing" to use the available computational power efficiently. Furthermore, module specific commands can be exchanged via this interface, e.g. the speech recognition module can receive a grammar as input and return the answer of the user as a result.

Image and Audio Processing. The RTDB manages different image and audio processing modules covering simple video-writers and audio-recording up to sophisticated gesture detectors and the integration of a commercial speech synthesize and recognition framework.

3.3 Person Identification

We determine the identity of the human interaction partner from a frontal face image, which is easy to obtain in the introduced dialog situation. The face position within the image is determined by applying the algorithm of Viola et al. [17] and is extracted and then scaled to a size of 64x96 pixels. The subsequent feature extraction consists of a rectangular windowed 2D Discrete Cosine Transform (DCT). The sampling window is moved in the vertical direction first, then in the horizontal direction. With each displacement the window is moved not by a full window size but rather one fourth of the window size so that an overlap of 75% to the previous window arises. To preserve the 2D structure of the images, a special marker is inserted at the beginning of each row.

For the classification process the following maximum likelihood decision is used:

$$\delta^* = \operatorname{argmax}_{M \in DB} P(X|M) \quad (1)$$

In this formula, X is the feature vector sequence of an unknown image and M represents one HMM of an individual contained in the database. The system recognizes the image as belonging to the individual whose corresponding model δ yields the highest production probability $P(X|M)$. To solve this equation, the values of $P(X|M)$ for all models have to be computed.

We evaluated the system on the FERET database that is provided by the Army Research Laboratories. Comparing the results of the discrete and continuous systems the discrete systems outperforms the continuous systems with a recognition rate of 98.13%.

This implies that only 6 individuals of the 321 tested are not recognized correctly. The computation time while classifying the discrete models was just about half the time of the continuous ones. This is important, because in real-world scenarios the robot has to adapt to new persons quickly.

3.4 Head Gesture Recognition

Models based on the analysis of face images impose knowledge about the object of interest and reduce the large amount of image data to a small number of expressive model parameters. We utilize a rigid, 3D model of human faces in our system, because it inherently considers position and orientation of the face in space. The 3D model is fit onto the face in the image to determine corresponding model parameters. The small amount of model parameters guarantees a short calculation time which in turn provides real-time capability. Five model parameters are considered to train a classifier for the recognition of head gestures. The data vector d_i extracted from a single image I_i is composed of the in-plane transition of the face and the three rotation angles (pitch, yaw and roll). However, we do not utilize the absolute values of the five parameters but temporal parameter changes. Due to their time-sensitive nature, we apply continuous HMMs for classification.

In total, fourteen different persons constitute the model for classifying head gestures. We record two sequences per person and head gesture (nodding, shaking, neutral). The model is tracked through these short image sequences consisting of roughly $n = 12$ frames I_i , $1 \leq i \leq n$ and the model parameters are exploited to train a classifier. Per training image sequence we create one set of data vectors (d_1, \dots, d_{12}) of fixed size. Each of these sets form one observation to train the HMM. Note that therefore the HMM determines the head gesture for a sequence of images rather than for a single image. In total, we present $14 \times 3 \times 2 = 74$ observations to the HMM. The only parameter given manually is the number of states J . We train different HMMs to correctly determine this parameter. Inspection of the training errors shows that the best parameterization is $J = 5$ [18].

3.5 Robotic Head

In this system a robotic head with 23 DOF is used for intuitive, natural communication feedback. In order to achieve dynamic, continuous, and realistic emotional state transitions, the 2D emotional state-space based on the circumplex model of affect is directly mapped to joint space corresponding to particular action units of the facial action coding system (FACS). It is also possible to display the six basic emotions according to Fridlund, Ekman and Oster [19]. The head is largely developed and manufactured in a rapid-prototyping process. Miniature off-the-shelf mechatronics are used for the face, providing high functionality while extremely low-cost. The active vision system consists of two firewire cameras, which are integrated into the eyes (2DOF each), forming a stereo pair with a baseline of 12cm and 30fps at a resolution of 640x480 pixels, and a 5DOF neck.

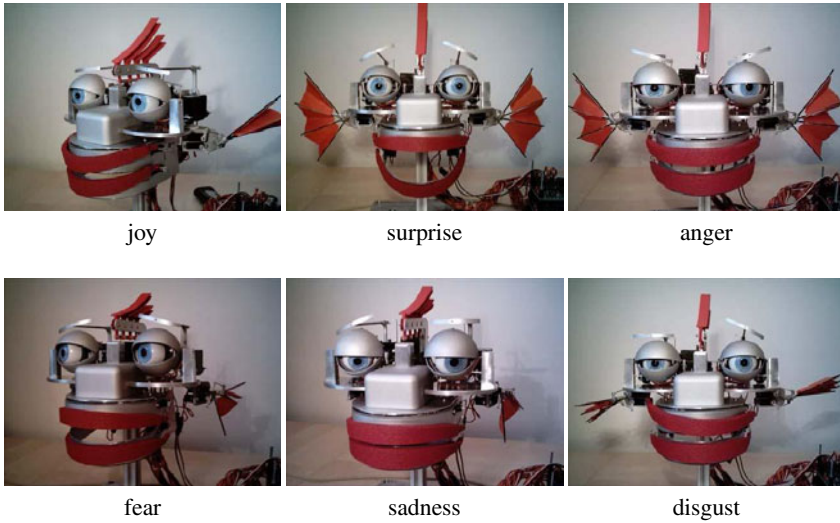


Fig. 3. Robotic head displaying the basic facial expressions

3.6 Facial Design

Facial action coding system. In order to get an objective distinction among traceable changes in facial expressions, the FACS based on face muscles [20] is applied. For this purpose FACS defines smallest movable units, the so called action units. The limitation on visually distinguishable changes in faces leads to the definition of 44 action units [21]. The current construction covers 13 of the total 21 action units needed for the basic emotions. For an even better match, the integration of a flexible skin would be required.

3.7 Emotion Models

Discrete emotional states. The existence of universal emotions, being represented and interpreted equally in the whole world, is said to be assured. Fridlund, Ekman and Oster affirm in their literature research in 1987, that six basic emotions are clearly identified in a multitude of different cultural groups. Joy, surprise, fear, sadness, anger and disgust, therefore, are considered universal [19]. Therefore these emotions are highly suitable for this scenario. Figure 3 shows the display of these emotions by the robotic head.

4 Conclusions and Outlook


In this paper we present a system that realizes a simple dialog between a human and a robot. An early version of the proposed system has successfully been shown as a live demonstrator at the *1. International Workshop on Cognition for Technical Systems*. Furthermore, a user study has been conducted to show the degree to which humans can understand the facial expressions of the robot [22]. More experiments are scheduled. Two different communication channels are regarded: The machine receives simple

commands and asks for confirmation via spoken language. Furthermore, head gestures are recognized via model-based image understanding techniques and classification with HMMs. The system operates without manual control and all important algorithms base on objective machine learning techniques instead of subjective manual design. For obtaining a more natural dialog, the system is capable of identifying its counterpart with an algorithm for person identification. Furthermore, the robots head is able to express different kinds of emotions for user feedback and reflect internal system states towards the human.

Objective of this first system is the implementation of an integrated framework for the recognition of user feedback resulting in a mostly natural human-robot dialog system. As such, there are now several ways to further improve the overall process and its performance. The first major step is to further exploit the existing implementation of a face recognition/verification module to track the user. The second major research topic is the expansion and improvement of the head gesture and facial expression classification system to include hesitation or confusion.

Future work also focuses on increasing the robustness with respect to real-life scenarios (lighting conditions, multiple points of view, etc.) and integrating facial expressions into the classification process. Thus the system might achieve an overall higher level of comfort and acceptance.

Acknowledgement

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Pseudo Swarm Implementation Using Robotic Agents and Graphical Simulation

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Abstract. The Pseudo Swarm Implementation aims to demonstrate the concept of swarm intelligence through the use of simulation and actual robotic units in hopes of recreating the complexity of natural systems. The actual swarm robots are modular in design and powered by PIC16f84 microprocessors. Each robot is composed of the motor module and a detachable sensor module. The motor module was constructed first and designed to handle basic movement and the random walk function. The sensor module was then designed afterwards which is capable of interfacing with the motor module through a universal protocol. The simulation platform was accomplished through the use of ActionScript3 to graphically depict the swarm behaviors given certain rules and a controlled environment. The simulation's purpose is to complement the data by creating robot objects similar to the actual robots and reproducing a larger number of them in a given environment. This work is a comprehensive study on a variation of the of swarm intelligence implementation of how a complex system may be composed of simple units defined by basic state machines.

Keywords: Swarm Behavior, Swarm Robotics, PIC16f84 Microcontroller, ActionScript 3.0, State Machines.

1 Introduction

Despite all of these advances in robotics or technologies in general, the use of increasingly sophisticated technologies have proved to be impractical due to increased costs and risks. Having reached this apparent limit in technological advancements, it is time to return to the fundamentals and natural designs of our world that have withstood both time and man. These natural designs or systems are what can be referred to as collective or global consciousness apparent in most basic life forms such as ants, termites and even microorganisms. Utilizing basic entities and intelligence, a cooperative network or structure, with the potential to accomplish communal goals or tasks, is created through the interactions. Perhaps it is possible to adapt these primal structures into the development of technologies today.

The aim of the paper is to simulate Pseudo-swarm Intelligence. The term "Pseudo" is coined due to the nature of the robotic agents to be developed. With the aim to develop low cost actual and simulated robotic agents and to remain faithful to the

interaction of natural systems, direct wireless communication between robotic entities or agents is non-existent. Similar to the behavior of most agents of natural systems, these robotic agents rely on sensory data to be able to communicate and interact or react with stimuli from their environment.

The robotic agents are driven by PIC microcontrollers and are composed of three general modules: processor module, motor module and the sensory module. The sensory modules would consist of proximity and light sensing capabilities. With the sensory module being replaceable and the microcontroller being reprogrammable, robotic agent can be modified to be able to accomplish certain tasks or to demonstrate certain state machines.

The graphical Pseudo-swarm environment simulation is powered by Action Script 3.0. The simulation program is capable of producing a specified number swarm of agents to implement the same state machines governing the behaviors of the robotic agents. This part of the implementation addresses the limitations presented by the hardware in terms of number, consistency and apparent costs.

2 System Configuration

2.1 Robotic Agent

The swarm robot is composed of two primary modules. The primary modules were the Control or PIC Module and the Motor Module. Several sensor modules may be used to expand the functions and general capabilities of the swarm robot.

The swarm robots embody finite state machines of a minimal number of states. The common component state in most state machines was the “idle” behavior which was either the random walk routine or a no operation routine. As purely responsive agents, excitation of the states through the sensors expansion modules served as triggers to state shifting of the swarm robot.

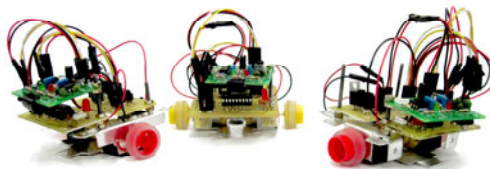


Fig. 1. Pseudo Swarm Bot Proximity Configuration

2.1.1 Control Module / PIC Module

The Control Module / PIC Module was mainly composed of the detachable PIC16F84A microcontroller. The PIC Module was designed to be similar to microcontroller trainer boards without onboard means of reprogramming the installed microprocessor. Reprogramming the installed microprocessor required the extraction of the microprocessor from the chip mount.

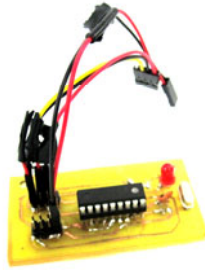


Fig. 2. Pseudo Swarm Bot Control Module

2.1.2 Motor Module

The Motor Module was mainly composed of a detachable L293D Motor Driver. The main function of the Motor Module was to serve as both the motor control and the power regulator of the entire swarm bot.

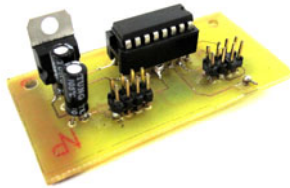


Fig. 3. Pseudo Swarm Bot Motor Module

With the available power lines and numerous configurable input pins from the PIC module, additional modules can easily be incorporated into the swarm robot. Examples of such sensor module expansions would be the proximity sensor and the LDR light sensor.

2.2 Simulated Pseudo Swarm Environment

For the initial tests, Action Script 3.0 is used to implement some pseudo-swarm algorithms. These algorithms are conceived and based from the limited functionality of the actual robotic agents. Pure frame-based events are used in the simulation.

2.2.1 Simulated Pseudo-Swarm Robot Design

The simulated swarm robot is composed of two objects: the Sensor object and the Body object. Combined, these two objects simulate a pseudo-swarm robot.

The swarm robot “sees” something whenever an object overlaps with the Sensor object. Likewise, it is seen whenever a Sensor of another robot comes across with the body object. There would be more complicated detections in the upcoming sections, but this basic concept is used all throughout.

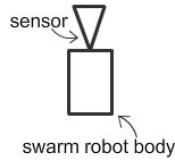


Fig. 4. Simulated robot composition

The concept of rotating the swarm robot is simple. The Body and Sensor objects are placed within the robot such that the center of the Body object is the center of rotation. Whether the robot would turn clockwise or counter-clockwise is set randomly at the start by the environment.

2.2.2 The Environment Design

The simulated robot agents are put inside an environment wherein they would interact with other swarm robots and the environment itself.

The environment is composed of a bounding box and the robot agents themselves. The robot agents, through their Sensor objects, are able to detect the Boundaries and are able to react to it.

Introduction of elements like Light and Food will be added later on to simulate more complicated algorithms.

The environment also incorporates rules like the speed and the rotational speed of the simulated robot agents. It also determines the number of robots inside the arena. It also makes sure that the initial positions of the simulated robots are distinct, such that the robots do not overlap one another

2.2.3 Pure Random Walk with Clumping

The first algorithm simulated by the group is the pure random walk algorithm. It consists of robots moving randomly inside a closed fixed space defined by the boundaries set in the environment.

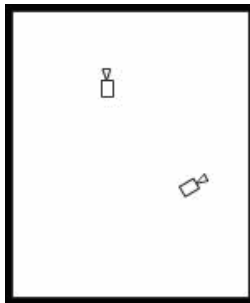


Fig. 5. Environment setup concept

Whenever these robots detects one another, it stops and waits for a random time, then checks if there is no obstacle. If a robot is in the way, it waits again for another random time. If there is no robot in the way, it continues moving forward. Eventually,

two simulated robots would have their Sensor object overlap with the body object of the other, thus refreshing the wait time indefinitely. They would never move from their positions while the simulation is running. These two robots would form the beginning of a clump. This implies that if a third robot would happen to pass by and detect any of the first two non-moving robots, it would wait too for an indefinite amount of time, and so on.

Table 1. Agent State Machine for Clumping

State	Action
0	Robot moves forward, stop while waitTime > 0
1	Robot detected a Boundary object, do rotate action

2.2.4 Pure Random Walk with No Clumping

The group has also created a version of the random walk algorithm with no clumping. Majority is the same with the earlier algorithm, however with this algorithm, while the robot cycles through its waiting time, it moves backward at a set speed provided by the environment variable.

Table 2. Agent State Machine for Non-Clumping

State	Action
0	Robot moves forward, move backward while waitTime > 0
1	Robot detected a Boundary object, do rotate action

2.2.5 Light Detection, Clumping at the End of the Light

This algorithm introduces the Light object. Having the Light object simply requires an extra robot state in the simulated robots, in addition to their default random walk process.

This algorithm does not use the Sensor object of the robot because the actual built robotic agents have the option to attach additional light sensors. Therefore, the trigger must be when the Light object makes contact with the body of the simulated robotic agent. Once this occurs, the robotic agent will cycle through two states to maintain its position within the lighted area. While within the lighted area, the agent will continue moving forward. However, upon leaving the area, the agent will then retrace its steps until it finds the light trigger once again.

Table 3. Agent State Machine for Light Detection

State	Action
0	Robot moves forward, move backward while waitTime > 0
1	Robot detected a Boundary object, do rotate action
2	Move the robot backward, placing it in the light.

2.2.6 Line Attempt Algorithm

This algorithm attempts to make the simulated swarm robots form a line out of the detection and communication limitations of the pseudo-swarm robots' set-up. In this attempted algorithm, the robot agents react to a "Food" trigger. Once an agent detects the trigger, the agent halts all activities and produces its own area with the same characteristics as the initial trigger. The end result would then be extending trigger area and an elongated version of the results of the clumping algorithm.

Table 4. Agent State Machine for Line Attempt

State	Action
0	Robot moves forward, move backward while waitTime > 0
1	Robot detected a Boundary object, do rotate action
2	Stop robot in the tracks, generate a SensorField around the object

3 Results and Discussion

Four robotic agents were constructed and tested for random walk, random walk with light seeking and random walk with proximity sense trials.

3.1 Robotic Agents

The random walk routine, whose permutations were predominantly forward, produced different results per swarm robotic unit. Despite having the similar high and low seeds in the programs of the four swarm robots, each one behaved differently. Each unit demonstrated varying bursts of displacement per movement routine. These tests are usually terminated once the agents are rendered immobile by corners or other robotic agents.

The units were then fitted with proximity sensors. This enhanced the test length to last the entire run of the battery life as units were able to avoid both the boundaries and other obstacles while displaying the same random burst movements.

Light seek and clumping was also on configuration which was tested. With the custom built light sensors, the robotic agents were able to find the lighted portion of the field. Success rates, however, were reduced due to limited battery life.

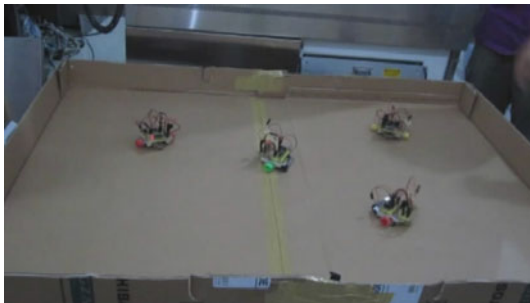


Fig. 6. Simulation Trial Demonstrating the Random Walk Routine



Fig. 7. Simulation Trial Demonstrating the Light Seek Routine

3.2 Simulated Robotic Agents

The simulated environment was able to recreate the conditions of the robotic agents trials. The simulations, however, were limited by the hardware the platform was running on. Due to the incapability of the programming language used to pipeline functions and allocate proper memory units, the simulation environment, run in a relatively high end laptop, can simulate up to 50 agents before experiencing lag. The more complex algorithms demonstrated an even heavier toll on the computer hardware.

Despite the platform handicaps, the simulated environment and agents, particularly the random walk with clumping algorithm, was rerun and confirmed to produce consistently random outcomes.

The other algorithms also produced uniformly random outcomes. The Light Detection and Clumping Algorithm were effectively able to collect the agents at the light boundaries to form a makeshift wall.

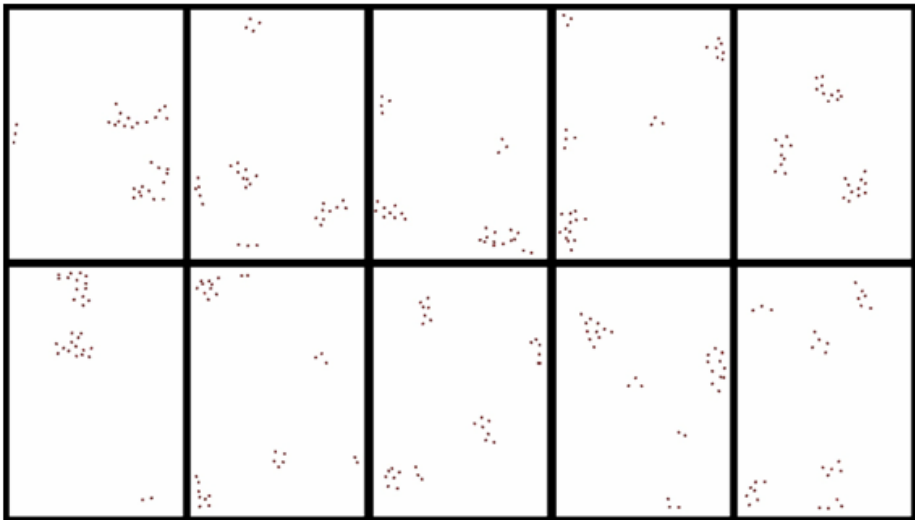


Fig. 8. Simulation for Random Walk and Clumping Algorithm with 30 agents

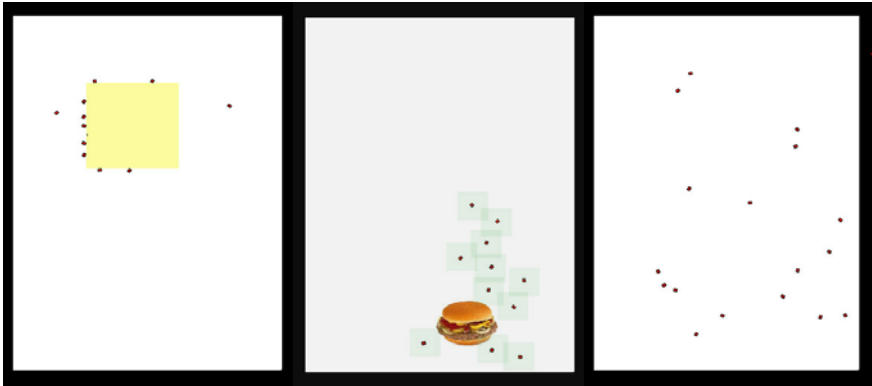


Fig. 9. Simulation Platform demonstrating Light Detect, Line Attempt and Random Walk

The initial random walk state, found in all algorithms, served to be a relatively effective search mechanism for the robotic agents. By increasing the number of robotic agents, the agility of the swarm to locate a particular trigger is also increased.

The Line Attempt Algorithm as well was able to form elongated clumps mimicking that of a line. This, however, would vary given a much larger environment or a differently sized food trigger object.

4 Conclusion and Recommendations

The natural order is almost always composed of numerous agents enclosed within a given an environment. Often times, these natural orders or systems demonstrate a consistent degree of uniformity amidst complexity that our own artificial systems are incapable of replicating.

The study of swarm or pseudo swarm intelligence gives new avenues of understanding these natural systems and how these natural systems can be used in different fields. Swarm intelligence or the concepts thereof have a place in both software and hardware designs.

For robotics, swarm emphasizes the use of basic units thus lowering the cost and increasing the robustness of a fleet or system of autonomous machines. The dispersal and clumping capabilities of swarm robotic agents can be applied physically to other tasks such as fire seeking, oil spill cleaning and search and rescue. For the medical and biological fields, swarm intelligence may be observed in the behavior and characteristic of most simple cellular organisms. From the bacterial level to the level of most colony life forms as termites and ants, swarm intelligence provides a means of completing tasks or goals with the use of simple rules and conditions from which an organizational structure composed of far more numerous states and possibilities may emerge.

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User Identification for Healthcare Service Robots: Multidisciplinary Design for Implementation of Interactive Services

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Abstract. Human robot interaction (HRI) is core to the design of service robots. The interaction during a service application determines how a user perceives the robot, which affects the user's experience and how well the user accepts the robot and its services. During the last decade, robotics service applications in close proximity to human users have been a popular research area. Research in related fields such as computer vision has also made significant advances to make available many interaction algorithms for HRI. However, we argue that there is only minimum utilization of these algorithms in the construction of HRI needed in actual service robots, despite their availability. This is partly because these algorithms have inherent limitations and only solve some of the HRI issues required in a complete service scenario in real environments. In this paper, a new general design approach is proposed to utilize modeling languages UML and UMLi to describe a service scenario and model the HRI required in a complete service. These models can be further used to elicit sometimes hidden HRI requirements from limitations in the interaction algorithms used. This approach helps multidisciplinary research to make HRI design decisions early at the design stage and guide implementation by software engineers. A user identification service scenario was designed, implemented and used as the case study of this design approach. It was integrated with a medication reminder application on a robot which was deployed and evaluated with the older people in a retirement village in New Zealand.

1 Introduction

With recent advances in computer and sensor technologies in the last few decades, service robotics has become a potential solution to various fast rising demands in society. Due to the aging population, there are rapidly growing healthcare and social demands especially in developed countries [12,11]. These demands promote research to provide solutions in various area to improve the quality of life of older people and also people with disabilities. Research in this area includes the development of personal and domestic robots for different types of assistance and healthcare services, companionship and social interactions.

In these potential service applications for robotics, design, modeling and implementation of natural human robot interaction (HRI) is one of the most

challenging problems. HRI in service applications for human users is inherently social. Unlike human computer interaction (HCI) which requires users to adapt to a computer user interface, HRI in service robot applications requires robots to communicate and interact in a human-like social manner. This means that robots must perceive natural social cues from human users, such as facial expressions and gaze, and respond with “anthropomorphic” social cues [5]. In addition, robots also need the ability to simulate human cognitive processes to reason about and control the delivery of the cues for human-like interaction.

There are many unique aspects to HRI especially in the context of delivering healthcare services, and these require multi-disciplinary collaboration between experts from different backgrounds including psychology, cognitive and health sciences [15]. To create a user-acceptable robot design for successful delivery of the intended services, there is a need for a design approach that facilitates these collaborations. Robot systems must be designed from top level system functionalities to provide services and at the interaction level which allows multidisciplinary issues in HRI to be exposed and addressed by a collaborative group.

However, some traditional software engineering approaches which have been successful in recent years in the construction of complex software system, are not so suitable in this setting. UML is an industrial standard defined by OMG (Object Modeling Group) for analyzing and designing object-oriented software systems and structures [6]. Although there is still no single, widely accepted standard in robotics development, UML is the most commonly used modeling approach to describe and communicate software structure in robotics [15]. In an interdisciplinary collaboration, UML based use case modeling (use case description and diagrams) can be effective in visualization and effective communication of system top-level functionality. However, other modeling diagrams such as class and sequence diagrams are more useful for software engineers in design of underlying architecture.

Furthermore, UML diagrams have been found insufficient in modeling the interactivity and behavioral aspects of user interfaces for HCI. UML diagrams have often resulted in unnatural user interfaces and hence bad user experiences [13,10]. As a result, Pinheiro [14] proposed UMLi, a minimum extension to UML, to provide a better and more intuitive alternative to modeling interaction objects and tasks and to represent a user interface and its behavior, instead of the traditional and complex UML class diagram. As an extension, UMLi includes a new interface diagram to allow abstract representation of interaction objects and adds new notations to UML activity diagrams to simplify behavior modeling in user interfaces. In [2], Armato adapted UMLi to model interactive human robot interfaces on an environmental service robot, Dust-Cart. The robot interacts with the users mostly through a combination of verbal communication with visual information on its touchscreen.

In this paper, UML use case modeling is combined with UMLi activity diagrams in a similar approach to capture a robot’s functionality requirements for a service scenario and to model social interaction between robot and user. We aim to model social interaction in more depth. New interaction patterns are additionally defined and added to represent new robot social perception and

actions during an interaction. Through modeling of robot behavior, we also address some design issues at the cognitive level of interaction, including feedback, reaction time and multi-modal communication abilities of the robot. This imposes real-time requirements on the robot’s social perception abilities [4].

As a case study, this paper presents the development of a user identification service for a medication reminder application [1]. The identification service is used to demonstrate a new design process that facilitates interdisciplinary collaboration in HRI design. UML and UMLi design are further used to analyze the service scenario in more detail and to decompose designed HRI and robot behavior into interaction requirements. These requirements help the multidisciplinary team including engineers to make design decisions about how to use existing interactive algorithms that are not readily applicable in real service applications. The end result is a complete list of interaction algorithms to be used, plus necessary assumptions that will be useful to software engineers in system integration and implementation. Section 2 describes the target service scenario: a medication reminder to which the user identification service is integrated. This is followed by descriptions of the use case model of the service scenario and the UMLi activity diagram used representing the robot’s behavior in the interaction. Section 3 details the new design process and the analysis necessary to carry the design models to implementation. Section 4 provides the implementation details. The design approach is discussed in Section 5 with some details of the user trial.

2 User Identification for Personal Robot Services

Healthcare applications are user-oriented and involve personal private health information, so user identification is essential. In human communication, recognizing the conversation partner is one of the most basic abilities required. This process is more difficult to automate but can be achieved using human biometrics including finger, palm and voice prints [7]. The medication reminder service scenario starts with the robot visiting people in their rooms before their medication times. In their room, the robot will execute a simple procedure to remind them of their medications, and on request provide more information relevant to their medication. The aim of the user identification service is to identify a user sitting in front of the robot. Face recognition technology was chosen as the main technology because of its availability from our research collaboration with the Electronics and Telecommunications Research Institute (ETRI) in Korea.

2.1 UML Design

The UML use case model resulting from use case analysis is shown in Fig. 1 and the main use case is simplified and described below. The main group of users (the actors of the system) is older people who are on medication and may find the medication reminder useful.

1. The use case begins when a user touches “Start” on the touchscreen.
2. The robot prompts the user to sit down and face the robot’s screen.

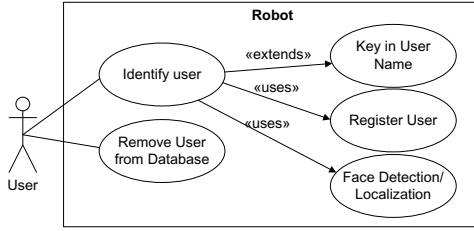


Fig. 1. Use Case Diagram for robot and remote PC

3. If the robot sees the user’s face, it gives visual/audio feedback and action feedback including centering its upper body and tilting its screen to a better angle to the user’s face. If the robot can not find the user’s face, the robot will keep looking until there is a timeout.
4. When the result returns, the robot prompts the user “are you (name)?” And asks the user to confirm.
5. If there is a timeout or the user rejects being the identified person, the robot falls back to ask the user to identify him/herself by entering his/her name on a keyboard on the touchscreen. This use case ends when the user confirms his/her identity.

Due to limited processing power on the robot, an additional remote PC is used in link with the robot for the image processing resources required for face recognition. This model is the intended deployment where many robots communicate with a central, powerful server. Building on the use case model, the robot’s behavior during the interaction is visualized in an activity diagram with the UMLi extension as shown in Fig. 2. In the diagram, there’s a notion of state for modeling robot’s interactive behavior as well as temporal dependencies between the interaction states and parallel activities for multi-modal interaction. In the interaction, two activities run in parallel: face recognition and speech/touchscreen interaction emulate the human cognitive process in communication, in order to engage in a conversation and identify the conversing partner at the same time. To include robots’ new capabilities for social perceptions and physical actions, more interaction patterns were defined in addition to the basic inputters and displayers (information from and to users during an interaction) defined in [2]. Three additional interaction patterns were defined to represent the robot’s perception of the user’s face including face location, size and user’s name (face recognition result). “Centering on face” was created to represent robot’s action upon detection of the user’s face toward the robot. These are shown in the interaction container (dashed cylinder) in the diagram. The robot was designed to give immediate feedback when it finds the user’s face because timeliness of robot’s responses upon user inputs or changes in robot’s internal state was found necessary to keep the HRI interesting and the user informed of the robot’s status [4,9]. For example, the robot responds to the user and says “Ah! I can see you” when it finds his/her face.

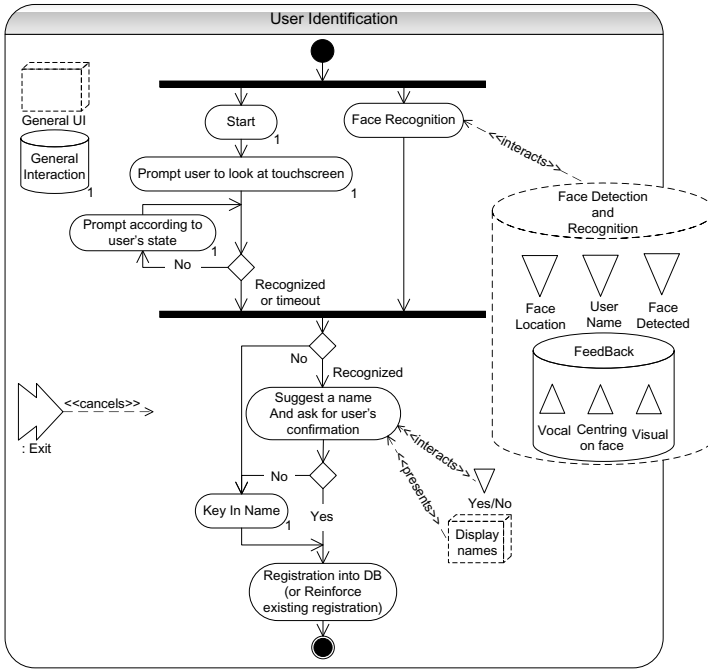


Fig. 2. Activity Diagram with new HRI interaction patterns using UMLi notations

3 Design to Implementation

Despite the availability of many HRI algorithms from other research areas such as computer vision, there are a considerable number of difficulties in utilizing these algorithms in real service scenarios with real users (except for algorithms that output binary signals such as face detection). First a simple real world scenario normally requires an integration of several modules; a single algorithm normally does not suffice. Second, there are inherent limitations in each HRI module and they might be critical to a robot’s interactivity and service delivery. In addition to that, an algorithm’s name does not necessarily fully represent what it can actually do and there are necessary conditions to realize the full advantage of each algorithm e.g. face and speech recognition algorithms. To bring these interactive algorithms into real use to construct meaningful HRI in a service scenario, it is essential discover these hidden requirements at an early design stage, before actual implementation, and include additional requirements implied by each HRI algorithm or module used in the design. Here, we propose a new design approach to elicit HRI abilities required in a target service scenario from UML and UMLi models. The list of requirements will help HRI designers in making design decisions in selecting HRI algorithms and modules for integration and in making necessary design assumptions. We argue that this process is needed, and would

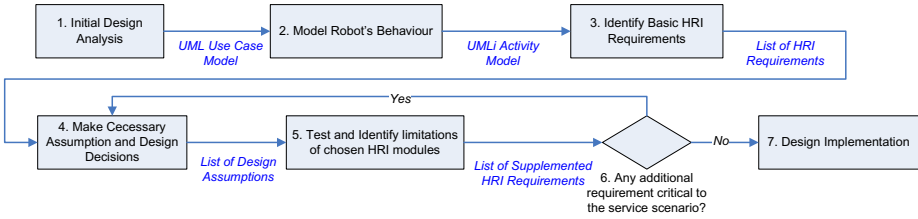


Fig. 3. Proposed Design Process Diagram

guide research better in system integration, data fusion, development of a single computer algorithm and service application in real world settings.

3.1 Proposed Design Process

As shown in Fig. 3, the 3rd step after modeling in UML and UMLi (1st and 2nd steps) is to supplement the use case model of the target service scenario to discover fundamental requirements on the robot's interactive abilities. The fourth step is to make design decisions on selecting algorithms for integration and determine whether design assumptions to be made are critical to successful delivery of the robot's service. Since each algorithm has its own limitations, each selected algorithm must be fully tested in order to draw out further design issues arising from its limitations, and include them in the design. This process should be iterated until all critical requirements are considered and solved.

In the case of the user identification service described above, the following list of descriptions was supplemented. To identify a user sitting in front of the robot, the robot has to have the abilities to:

1. Detect that a user is sitting down in front of the robot.
2. Search and detect where the user's head/face is in the camera view.
3. Detect whether the user is looking at the touchscreen.
 - (a) Detect the user's head orientation to the camera.
4. Recognize the user by unique features on his/her face.
5. Save the user's images and register the user to the database.
 - (a) Detect whether the user has left.
 - (b) Track the user's face.

The face detection and recognition algorithm was evaluated, and tested with results detailed in the next section. From the test, it was found out that the accuracy of the face recognition algorithm is largely dependent on the angle of the user's face to the robot's camera. Additional requirements arising from this and other issues were then added to the list (items 3(a), 5(a) and 5(b)).

Requirements 4 and 5 were satisfied by the face detection and recognition algorithm, which however depends on requirements 2 and 3 to give meaningful results. For requirements 1, 5(a) and 5(b), a motion detector and face tracker as well as other cheaper solutions were considered, to avoid issues that may arise

from the user leaving and entering during an interaction. The second requirement could be solved, since the face detection has reasonable tolerance to a range of face angles and the robot is capable of panning and tilting. The third requirement is probably the most critical as it affects the accuracy and hence usefulness of the user identification service. There was no head rotation detection algorithm available. An alternative solution was devised under the assumption that the user will at least look at the screen during his/her interaction, and then the robot could take some good pictures of the user's frontal face during these times, which corresponds to the detected face size during an interaction. This issue was further circumvented by filtering the recognition results over interaction time to extract recognition results when the user is looking toward the robot.

As HRI of higher complexity and longer duration is considered, many more design issues may arise and need to be solved. This design approach helps researchers involved in HRI design. It also helps engineers (a) clarify what assumptions are being made to make the service scenario possible, and (b) identify and match interaction requirements to interaction algorithms that are already available to developers. It is important to use an iterative process to identify HRI modules required and then find out further HRI requirements through testing on their limitations. The end result will serve as a guide for better integration of HRI modules for a target service application.

4 System Implementation

The user identification service was implemented and tested on a robot platform "Cafero" jointly developed by the University of Auckland/Auckland UniServices in New Zealand, with ETRI and Yujin Robot Co. Ltd., in South Korea. The robot hardware consists of a differential drive mobile platform, two single-board computers, sonar sensors, a microphone, speakers, a touch-screen mounted on an actuated head and a camera. This HealthBots project is a collaboration between professions from several disciplines including health psychology and aged care [1].

4.1 System Overview

The main components of the system are the GUI (Graphical user interface) and the face recognition system that run in parallel on the robot and a remote PC. The face detection and recognition algorithms used in this design are provided by ETRI as dynamic linked libraries (DLLs). The algorithms rely on facial features and hence are reasonably robust to illumination changes in the environment [8]. The face detection is able to detect a person's face robustly against head rotation up to about 30 degrees to both sides. This advantage however has to be traded-off during face recognition. The face recognition algorithm's confidence and accuracy are very much dependent on head rotation and drop significantly when the person turns his or her head more than about 10 degrees to the sides. The GUI on the robot's touchscreen was implemented in Adobe Flash and Actionscript. To facilitate customization and on-site modification of the GUI for the user, Actionscript was used to automate the process of creating flash pages

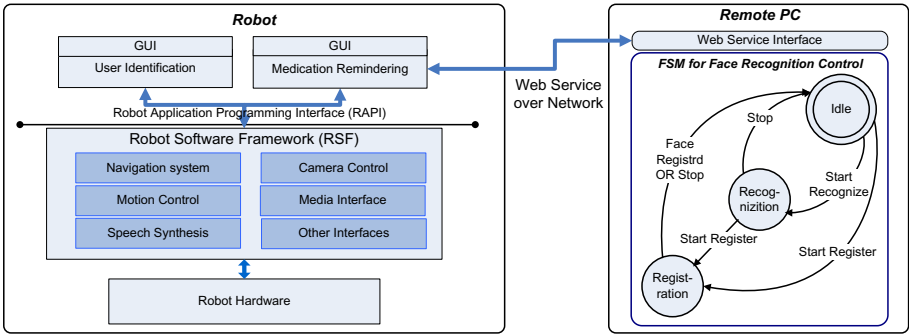


Fig. 4. Overview of the system implementation

and buttons and texts on it from an XML script. Through this automation, the developers were able to focus on the application flow of the user interface rather than other details on the GUI such as pictures and buttons.

The software system was implemented on a robot software framework through a Robot Application Programming Interface (RAPI) which allows control of several low-level functional module on the robot as shown in Fig. 4. Web services was chosen as the interface between the robot and remote PC. A finite-state machine control was implemented on the remote PC side which can be fully driven by the robot to start, stop and retrieve results through the web service.

The software architecture of the robot was designed in such a way that its distributed components are very loosely coupled. This allows independent development of each component and increases the overall robustness and security of the software, by isolating the components as much as possible [3]. Standard web-services were used to communicate between the distributed components, as they provide a high-level of isolation.

Web services extend the World Wide Web infrastructure to provide the means for software to connect to other software applications. Applications access Web services via ubiquitous Web protocols and data formats such as HTTP, XML, and SOAP, with no need to worry about how each Web service is implemented.

5 Discussion

The proposed design approach will be further applied to design other health care service scenarios including a vital signs monitoring service which involves the robot taking users through measurements of their blood pressure, pulse rate, blood oxygen saturation level, temperature and HRI needed to connect or initialize these scenarios; for example, the interaction required for the robot to actively approach users or just prompt users and wait for them to initialize communication and service. As more service scenarios are considered and more interaction algorithms are used, more interaction patterns will be added to represent the robot's perception/sensing abilities of social cues and physical actions.

However there are still limitations to this approach, some aspects of HRI are still not visible through the design process proposed in this research and are critical in user experience and acceptability. For example the UML & UMLi models are still very limited in description and visualization of timeliness of the robot's perception and physical actions. In the case of the user identification service scenario, temporary dependency between interaction states could be visualized but issues on timeout on face recognition and the waiting time for the recognition result (described in step 4 and 5 in use case description) could not be elevated as we wished. This factor and other factors such as expressiveness of its internal states (intentions) in human robot communication and physical interaction could also impact the interaction and the user's experiences significantly. However we argue that some of these design issues are hard to model and are sometimes revealed only through actual user study and evaluation with its intended users. In this aspect, we would like to emphasize the importance of completing the loop from design to implementation to evaluation and design reiteration to incorporate user feedback. The medication reminder application was tested with young to middle-aged participants in the University of Auckland as a pilot test. It was then taken to a retirement village for a trial with 10 older participants. The robot is driven manually to the participant's room where the robot takes over to initialize interaction with the participant, first by identifying them, and then ask them to take their medicines. User feedback and interaction experience were evaluated based on questionnaires after interaction.

The current user identification procedure can still be improved. For example, if the wrong face is identified, then there must be a process for user to correct it, by asking for direct confirmation or by requesting the user to select one of a number of close matching images. Additionally, since user identification is so important in healthcare the identity should be confirmed using another method, for example by comparing fingerprints or palm prints.

6 Conclusion

In development of an interactive service application to identify a user and remind him/her of their medication through a robot, this paper proposed a new general design approach to capture top-level system requirements of the robot, model robot's HRI during service and then analyze the HRI into a list of requirements. Utilizing existing software engineering approaches UML and UMLi, this new design method aims to facilitate interdisciplinary collaboration to address issues in HRI. In order to model social, cognitive and physical interaction aspects of HRI, interaction patterns for new social perceptions and physical actions were defined. Including algorithm testing in the iterative design process, this method helps software engineers in utilizing them in real service application and make design decisions in consideration of their limitations. This approach will be further used in other service applications under development to investigate its usefulness and limitations.

Acknowledgment

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Using a Social Robot as a Gaming Platform

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Abstract. As social robotic research advances, robots are improving their abilities in Human-Robot Interaction and, therefore, becoming more human-friendly. While robots are beginning to interact more naturally with humans, new applications and possible uses of social robots are appearing. One of the future applications where robots will be used is entertainment. This paper presents a social robot as a development platform for which several robotic games have been developed. Five of these games are presented and how these games take benefit of the robot's HRI abilities is detailed.

Keywords: Social Robot, Edutainment, Robot Games, Robot Entertainment, Human-Robot Interaction.

1 Introduction

Social robotics is an expanding field where research is focused on employing social robots to perform social tasks such as entertainment, education or a combination of both of them, *edutainment*.

Many robots have been designed with the aim of being used as an entertainment robot. One of the most famous toy-robots is Aibo [1] which main goal is to behave like a pet and play with persons for accompaniment. TOMY Company has developed I-SOBOT. It is intended for entertainment purposes: it can be controlled by voice, it is capable of speaking more than 200 words and phrases and it has more than 200 pre-programmed actions. Pleo robot plays a very basic game called tug-of-war and it is just a substitute pet. NEC is also researching on entertainment robots with Papero. It performs dances, mimicry, riddles, quizzes, fortune telling and other games.

Other works try to mix entertainment and education in robotics leading to edutainment robots. In [2], preliminary experiments on remote education have shown that students interact with robots showing pleasure and interest. [3] describes how children play with Roball, a plastic spherical robot, in an adaptive mode increasing and sustaining interaction.

Also, it has been shown that robots have a psychological effect on patients, improving their motivation, as is demonstrated with the Paro robot. Furthermore, children that suffer from severe disabilities use robots with the aim to learn and improve their quality of life [3],[4]. Depending on the games, the robots will help the users to develop and improve their abilities.

Almost all presented robots are equipped with a limited number of games or applications. Moreover, it is difficult to add more functionalities to them. The lack of such software flexibility results in robots with shorter life cycles than robots which have the capability of running more software applications. For example, in the case of toy robots, a robot which is capable of playing several types of games can be addressed to a wider range of people than other robot with a pool of few games.

In this work we present an easily expandable robotic platform for the development of board games as well as educational applications. The platform consists of the robot Maggie [5] and its software architecture as the base for the creation of several game skills that allow the robot to play board games.

The paper continues in the next section with a short description of the robot Maggie. We describe the hardware and software platforms used and we detail which are the interaction capabilities of the robot. Section 3 presents the interaction mechanisms of the robot. In section 4 we discuss the robot as gaming platform and present a description of five of the games that we have developed. Finally, in section 5 a brief conclusion and future issues are discussed.

2 Description of the Robot

The robot Maggie [5] is a platform for studying human-robot interaction (HRI). The development of the robot is focused in finding new ways to adapt the robotics potential to provide to human users new ways of working, learning and entertaining.

2.1 Hardware

Maggie is designed as a 1.35 meters tall girl-like doll. Its base is motorized by two actuated wheels and a caster wheel. The base is equipped with 12 bumpers, 12 infrared optical sensors and 12 ultrasound sensors. Above the base, a laser range finder (Sick LMS 200) has been added. The upper part of the robot incorporates the interaction modules. On top of the platform, there is a robot head with an attractive design. The head has two degrees of freedom, while each arm has one degree of freedom (DoF). These features are illustrated in Fig 1.

Maggie is controlled by a main computer hidden inside her body. In the computer resides the software architecture of the robot. For image acquisition, the robot has a camera located in the robot's mouth. The camera is a Logitech QuickCam Pro 9000. The robot has touch sensors on the surface of the body and a touch screen situated on the chest. Finally, inside the head, an RFID antenna is placed to identify objects.

2.2 Software Architecture

The software architecture of the robot is the Automatic-Deliberative (AD) architecture [6]. AD is composed of two levels, the automatic level and the deliberative level. The automatic level is where the low-level control is done: in the automatic level, the modules that provide communication and control of the sensors, motors and other hardware are located. At the deliberative level, reasoning and decision processes are placed.

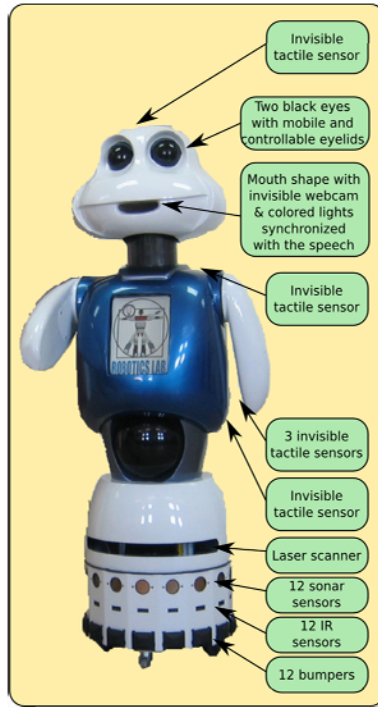


Fig. 1. The hardware equipping Maggie

The essential component of the AD architecture is the skill. A skill is an entity with the capacity of reasoning, processing data or carrying out actions and with the capability of communicating with other skills. For example, the *laserSkill* manages the laser range finder of the robot, formats its data and shares it with the rest of the skills. The other skills can benefit from the data obtained from the *laserSkill* to, for example, build a map and share it with other skills. A detailed description of the AD architecture can be found in [6] and [7].

3 Interaction with Maggie

Maggie is a robot designed and created to interact with humans, therefore its goal is to explore the mechanisms of interaction with humans. At present, the robot has several mechanisms of interaction that we analyse here. All of the following interaction mechanisms can be used by the games to improve the perceived experience of the human while it is playing with the robot.

a) Voice System: The most important interaction mechanism of the robot is the voice system. This system allows the robot to speak and to listen to humans. The voice system is composed of a set of skills that gives the robot a complex and powerful system of communication. The main voice skills are: Automatic Speech Recognition

(ASR), Emotional Text To Speech (eTTS), Speaker Identification, Voice Tracker and DialogueSkill based in VoiceXML. The voice generator and voice recognition are provided by a professional software vendor Loquendo wrapped into the global architecture of Maggie as a skill.

The robot voice is generated by a Text To Speech (TTS) system which allows the robot to convert any written text to human voice. It can generate voices in Spanish and English with high quality and several emotions. The voice is clear and easily understandable by humans. Moreover varying the voice tone, the robot can communicate with expressions and emotions as happiness, sadness, tranquillity or excitement. It is also possible to generate laughter, yawning and sighing, which are very useful in games.

The robot is also able to understand what we say. The human communicates with the robot through a wireless microphone and it is understood by Maggie with a speech recognizer using a grammatical based knowledge system. Using this skill Maggie can understand Spanish, American English and British English. Any human can talk to the robot in natural language and a training phase it is not needed.

Currently, all the interactions are performed following two paradigms of HRI, the master-slave and the peer-to-peer (P2P) paradigms. Depending on the context, the interaction will lead to one or the other paradigm. In the master-slave paradigm, the human acts as the master and the robot obeys the commands expressed by the human. In the P2P both human and robot interact as equals. The first is used in normal contexts where Maggie acts as a personal assistant. The second is mainly used in games contexts where the human and the robot play games acting as rivals or partners depending on the game.

Maggie is also able to identify the person which is talking to her using a previous recorded voice-print database. This capability is called Speaker Verification and is powered by the Loquendo speech system.

All these skills are controlled by the dialogueSkill (in a higher level of abstraction) and it is based in VoiceXML.

b) Touch sensors: Maggie can sense when a person touches certain parts of its body (head, arms and upper body). The robot has a dozen capacitive touch sensors placed over her body. This skill is always running and always detects when a human touches a sensor. It is very useful in games as another interaction mode.

c) Computer Vision: The robot has a camera in its mouth which enables her to “see” its environment. The vision system captures the images from the camera and processes them with the OpenCV library. The processed data can then be used by several skills, for example: detecting a person, counting the number of people in the environment, detecting the game board, etc.

d) Radio Frequency Identification (RFID): Another mechanism to interact with the environment is using Radio Frequency Identification (RFID) tags [8]. Although it is not a naturally type of interaction between humans, it allows the robot to identify and retrieve information about several objects that are presented to the robot by the human. Maggie has a RFID reader in her body. This reader can read radio frequency tags inserted in objects. When the human presents the object to the robot, the robot is not only able to identify the object itself, but also is able to retrieve more information related to it. We have developed several skills that use this kind of interaction: reading and retrieving information about certain products like drugs and toys. Note that many

utilities developed with this identification system may be processed either by the vision system or the RFID detection system. While the first is similar to the human sensors, with the second it is easier to develop new applications which are more robust to certain conditions like low light rooms, etc.

4 Gaming Platform

Maggie is able to play several games thanks to the design of her software architecture. Since AD enables the construction of new skills that make use of previously built skills, the development of new games becomes a task where most of the work has already been done by other skills. For example, to create a new game, it is possible to use the vision skills data to locate the game board and process the current state of the game. After that, the new game skill can calculate the next movement and use the communication skills to tell the human which is going to be the robot's next movement. In other words, creating a new game consists in developing the algorithm of the new game, and after that complement it with the necessary skills to allow the robot to interact with the world and the human player.

The robot interaction capabilities can also be used to allow the robot to play board games with humans in the same manner humans play with other humans. For example, the voice system is not only used during the games. During the complete operation of the robot it can be operated by voice. The robot understands several dialogues that allow the user to activate and deactivate by voice the available skills like the games or other robot utilities. Our aim to have the robot completely operated by voice pursues producing the feeling of interacting with other person.

The following sections show some of the games we have developed until so far to test the interaction capabilities of the robot and are an example of how to create a complex gaming robotic platform by the addition of several aggregated skills. Several of the described games are based in classical board games.

4.1 Peekaboo

This game is the robotic version of the classical Peekaboo game. We first developed this game to test a face detection skill and then was integrated into the pool of games that Maggie can play. The human Peekaboo version is a game played with babies in which the adult hides her face with her hands or with an object. In the robotic version, a person hides her face from the robot in the same way as the classical version.

The purpose of the game is hiding the face to make it undetectable by the robot's computer vision system. If the robot does not detect any faces, then says that she can not see anybody. When the person shows her face to the robot, then tells that now she is seeing her. More than one person can play the game at the same time. In this case, the robot tells to the group the number of faces she is seeing.

4.2 Guessing a Character

In this game the human player must think on a fictional or real character. The robot asks several questions to the human until it is able to guess the character. The

questions require only yes/no answer. Usually in less than 20 questions the robot guesses the character.

Before starting the game, the robot describes the rules of the game and how the player must interact with the robot. Once the robot has finished the description of the game the player must have decided what the character will be. The game starts when the robot starts asking questions about the character. The robot asks the human using its voice system. The human also responds by voice and the robot has to analyse and detect the responses of the human.

The game is implemented as a skill that uses the robot's built-in wifi connection to connect it to a public web server (Akinator¹). This server has a database of many characters and the intelligence to relate the answers of the human with all the possible characters.

Using machine learning techniques and artificial intelligence the web service selects questions so that the answer eliminates as many potential characters as possible.

The implementation of the algorithm is based on a search tree. Each question eliminates the maximum number of options, filtering the branch that has more children

4.3 Tic-tac-toe

In this game, the robot and the human play the game *tic-tac-toe*. The game is played on a board of 3x3 cells. The robot can play either with crosses or circles. The player can start the game or let the robot do it. If the human starts the game, putting down a counter of one kind, the robot will use the other kind of counters. If the robot starts, it always chooses crosses.

The game is performed in the following way. Supposing the robot starts the game, it chooses a position and it tells it to the human. Because the robot lacks hands, the human must put the counter for it in the position the robot has asked to. After that, the human turn begins. The human chooses a free position, puts the counter on it and lets the robot know that he has finished. Once the human turn has finished, the robot analyzes the board with its vision system. After the analysis of the board, the robot has an updated status of the game so it can perform the next move.

The game ends when one of the players has managed to put three consecutive counters on the board (i.e. it has formed a row). In this case that player has won the game. The game also finishes if the board ends full and neither the robot nor the human player have managed to put three consecutive counters. In this case the game finishes in a draw.

The robot uses its vision system to recognize the game board. For that reason it must be mounted on a table near enough to let the robot see it (usually at 1m height and about 20cm from the robot).

The interaction between the robot and the human is done by voice. The robot tells the human the rules of the game, asks the human to put a counter in a certain position on the game board and updates the human with the state of the game (I.e. is finished, who has won, etc.). The human must warn the robot when he has finished his turn.

¹ Akinator is the name of the game, <http://en.akinator.com/>



Fig. 2. Maggie playing to tic-tac-toe

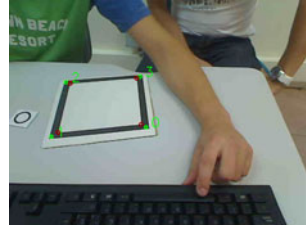


Fig. 3. Recognizing the board game

In order to recognize the play area (Fig. 3), the robot uses a vision machine algorithm that threshold the image and finds a black square which is the frame of the game board (Fig 4a). Once it has found the game board, it corrects the image from a perspective view to a plant view (Fig 4b). In the plant view the algorithm recognizes the game counters placed in the game board (Fig. 4c). These algorithms are based on the OpenCV libraries.

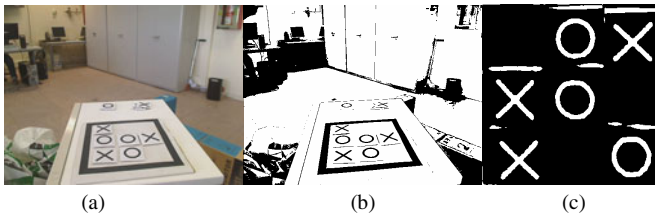


Fig. 4. (a) Board game (color perspective image); (b) Board game (threshold perspective image); (c) Image corrected in plant view

Once the position of the game counters is defined, it is necessary to apply an appropriate algorithm to decide the next move. The game algorithm is based on minimizing the “damage” that you can receive from the adversary and maximize your chances of winning.

4.4 Hangman

In this game, the human thinks of a word and the robot tries to guess it asking questions and processing a few clues given by the human. The human writes, on a piece of paper, as many underscores as letters the word has. After that, the human puts the piece of paper on the table to allow the robot to view and count the number of underscores of the word. The human can give the robot more clues, for example one or more letters of the word, written in the exact position of the word. For example, in the word “robot”, the human can write a “b”, but it must be placed just above the third underscore, which corresponds with the letter “b” of “robot”. Counting the number of underscores, the robot is able to know the number of letters of the word. If the human gives her a clue in the form of a letter, the robot has then more information of the word and can reduce the list of possible words.

When the human puts the paper with the underscores on the table, he has to tell the robot to start the game. Then, the robot tries to guess the complete word. To do this the robot has several rounds. In each round the robot must guess a letter of the word. If the proposed letter is in the word, the human must write it on the game board, just above the corresponding position of the word. The game ends when the robot guesses the word or when the robot reaches a maximum number of failures.

Like in the tic-tac-toe game, it is necessary to put the table near the robot to allow it to see the game board (Fig. 5). The human player is responsible for thinking of the word, and writing the underscores corresponding to the number of letters of the word in the game board. The robot is responsible of guessing the word. In each round the robot asks for a letter, and the human player writes this letter above the underscores that correspond to the letter in the word (in the case this letter is in the word). For example, in the word “robot”, if the robot asks for the letter “o”. The human must write an “o” above the second and the fourth underscores. Doing that, the robot is able to detect that she has guessed the letter and to detect that the letter appears two times in the word. If the letter is not part of the word a failure is considered. The maximum number of failures is six. The game ends when the robot guesses the word or when the six failures have been reached.

In each turn, the user must write clearly and with black marker the letters that the robot has guessed. Once the human has done this, he warns the robot to make another attempt using a voice command. After that, the robot analyzes the game board, counting the number of underscores and the letters that it has guessed. Again, both for character recognition (OCR) and to find the board game we use computer vision techniques based on the OpenCV libraries.

In Fig.6a, we can see the game board in the top right corner. In Fig. 6b the robot analyzes the image and detects the game board (square with big black border). In the Fig. 6c the robot has obtained the rectified image from the playing area (plant view) and has detected and identified the letters written on it.



Fig. 5. Maggie playing hangman

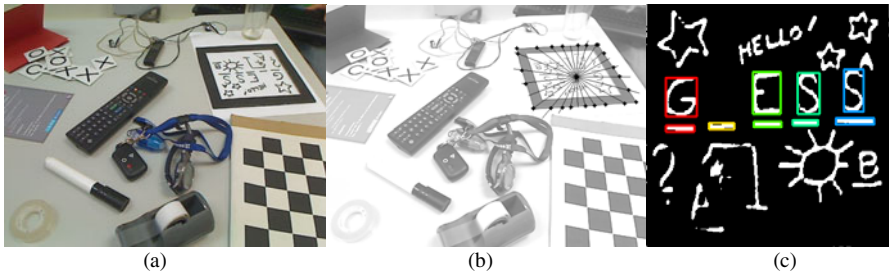


Fig. 6. (a) Table with the board game, (b) Maggie detecting the board game; (c) OCR in the rectified image

The algorithm used in the game is based on finding the words that can match with the current state of the game, those words are in a dictionary with the most common words of the language. We have two dictionaries of words, one in English and another in Spanish, each one with approximately 100,000 words. These words are the most common in both languages.

The human part of human-robot interaction in this game consists in writing in the board game and talking to indicate the end of each turn. In the other part the robot interacts with the human reading the writing of the human with its vision system and making questions to the human related to the game.

4.5 Animal Quiz

The aim of this game is to study the interaction between the robot and children using the voice system and RFID sensors.

In order to play to animal quiz we have ten soft toy animals with RFID tags inside of them. Each soft toy is an animal of one color and has a single unique name. There are not two soft toys that are the same animal, have the same color or have the same name. The game consists in Maggie asking a child to bring her one of the soft toys. To do that the robot asks for one of the properties of the soft toy (animal, color or name). The child picks the corresponding soft toy and brings it to the robot. The child gives the soft toy to the robot by bringing it near to the nose of the robot, where the RFID reader is located. This allows the robot to detect if the child has brought the correct soft toy or not. Writing and reading RFID tags in Maggie is explained in [8].

If the child has not understood the question she can ask the robot to repeat it. When the game has finished, the robot tells the number of right and wrong answers. Only the first time the child shows the toy in each question is counted as hit or failure.

When the robot asks for a soft toy, it waits until an RFID tag is detected. The toy must be placed close to the robot nose, typically 20 cm. The robot compares the number stored in the tag with the right answer in order to know if the toy is the correct one or not. The child may try to guess the soft toy again and again until he gets right.

5 Conclusions

In this paper we have presented a social robot with many interaction capabilities and its use as a gaming platform. We have presented the robot hardware and software architecture and its interaction skills. The presented robot software architecture facilitates the creation of robot applications such as games by composing previously developed skills into new ones. It is, for example, easy to create a game that uses the presented interaction capabilities of the robot to interact with the environment and with the human player.

A social robot with the capability of running applications is able to adapt to scenarios which were not initially intended or designed for it. In this way the life cycle of the robot can be increased considerably thanks to the constant development of new applications that at the same time could enlighten new scenarios and areas to where the robot could be used. In this case, the new area is the gaming area.

Following the exploration of this area, our future work consists on conducting experiments to study how people react and behave when they are playing with a robot that tries to behave in the same way a human would do in such game situations. The first data seems to indicate that people tends to be more involved when a robotic character shows emotions during the game. Also, our preliminary results show that robots with more interaction capabilities make people feel more comfortable and, as a result, they tend to spend more time playing with the robot.

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Robotic Platform: A XML-Based Extensible Robot Intelligence Architecture (XRIA)

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Abstract. This paper concerns the development of a lightweight robotic platform which targets at flexibility, scalability, extensibility and environment for intelligence embedment. The platform employs layered architecture and event driven communication paradigm which allows for efficient integration of additional sensory input and actuator control. New intelligent algorithm can be encapsulated into plug-ins and lodged into the platform to leverage the robot intelligence and learning capability. A multi-purpose XML engine is introduced for the control of system communication, business logic, finite state machine execution and decision making. The proposed robotic platform was deployed on a number of robots in our laboratory such as coffee serving robot and receptionist robot. The results show that XRIA is flexible, manageable and works well for different types of robots with required operating performance.

Keywords: Robotic software platform, Robot intelligence, Pluggable architecture.

1 Introduction

With the continuous advancement in sensors, actuators, mechatronics, especially artificial intelligence, robots are making their way into the world of our everyday lives. Many types of robots that human beings have fantasized about them now are becoming reality: bank tellers, telephone operators, vacuum cleaners, shop assistants, tour guides, housemaids, elder care nurses, play mates, surveillance robot, receptionists, etc [1]. Different from the industrial robots in the early days, which could only perform certain tasks automatically to improve factory quality and efficiency, social robots have attracted more and more attention. These social robots are employing a variety of sensors such as cameras, microphones, hepatic sensors, olfactory, etc. for better understanding of environments so that they can possess advanced social skills and high level intelligence when interacting with humans. One challenge which has become a big hurdle for the development of advanced robot is a generic robot architecture which can fit into a variety of robot platforms. This challenge for robotic platform is addressed by Bill Gates as the issues faced by personal computer industry three decades ago [2]: “The challenges facing the robotics industry are similar to those we tackled in computing three decades ago. Robotics companies have no standard operating software that could allow popular application programs to run in a

variety of devices. The standardization of robotic processors and other hardware is limited, and very little of the programming code used in one machine can be applied to another. Whenever somebody wants to build a new robot, they usually have to start from square one.” As we know, different robots have different input sensors, control actuators and come with different functionalities and behaviors. Traditional robot control software adopts proprietary architecture which is specific to a fixed number of inputs and outputs. The type of querying sensors and commanding actuators are also coupled into the software itself. In addition this kind of software system usually only integrates and coordinates the raw inputs and outputs rather than providing robot intelligence. If certain intelligent algorithm is provided in the software system, the system tends to use rigid structure which is hard for change of new control strategy.

In this paper, we present a lightweight robotic platform which targets to tackle the aforementioned challenges with particular focus on robot intelligence development environment and flexible robot business logic control. The platform employs layered architecture and event driven communication paradigm which allows for efficient integration of additional sensory input and actuator control. The platform provides a flexible and extensible architecture for robot intelligence development and integration. New intelligent algorithms can be encapsulated into various plug-ins and dynamically plugged into the platform to leverage the robot intelligence and learning capability. A multi-purpose XML scripting engine is employed to control the communication, business logic as well as decision making for flexibility and extensibility.

2 Related Work

Much effort has been put forth by researchers from both academia and industry in the research and development of generic robotic platform. The software giant Microsoft has brought the Microsoft Robotics Studio (MSRS) to the robotics community. MSRS can be used across a wide variety of hardware and supports various programming languages such as C#, Visual Basic.NET etc. for robot control and simulation. Concurrency and coordination runtime, visual programming language are some other features provided by MSRS [2][3]. However MSRS is windows only application tools, the learning curve is relatively high [4]. Player/Stage is another popular robotic platform with a big user community. It is an open source project with a widely used network oriented device server (Player) and two simulation back-ends (Stage & Gazebo). This platform features its support for multiple devices on the same interface, and on-the-fly server configuration [5], but it does not separate the control algorithm from main flow and it needs virtual driver for new algorithm and data generation [6]. MobileRobots comes with software API and its hardware but customized program needs proprietary robotic command language [7]. Another open source robot operating system is ROS [8]. ROS is relatively new platform which originated by the Stanford Artificial Intelligence Laboratory in 2007 under the name switchyard. It promotes modular and tools-based software development. ROS currently is under active development for various packages such as planning, perception, simulation, etc. There are many other more systems such as TeamBots [9], Miro[10], Evolution Robotics ERSP [11], YARP [12], OpenRTM [13] etc. They come up with different features. Detailed summary can be found in [4], [14] and [15]. However, one

important issue which has not been addressed by most of the existing systems is to abstract the intelligent functions from the robotic platform.

3 System Architecture

The proposed robotic platform adopts layered architecture for loose component coupling. It is composed of input/output layer, communication layer and intelligence layer. The system architecture is shown in Fig. 1.

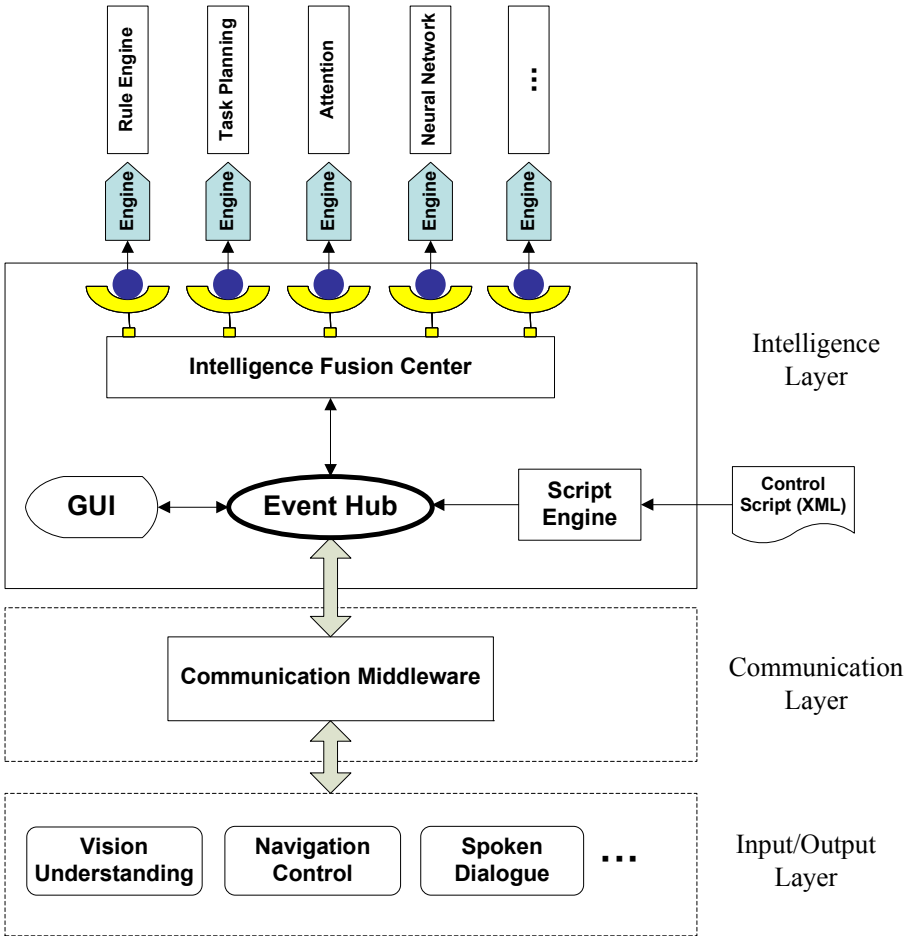


Fig. 1. Schematic diagram of robotic platform

3.1 Input/Output Layer

The input/output layer consists of a number of remote agents which complete required data inquiry and necessary preprocessing and feature extraction. The commonly used

remote agents for social mobile robots include navigation agent for path planning and obstacle avoidance, vision agent for the understanding of the scene by visual recognition, spoken dialogue agent for speech recognition and conversation, motion control agent for the control of robot arm and head control, Radio-frequency identification (RFID) agent for object information scanning, Ultra wideband (UWB) for accurate localization, etc. The individual input agent ties to one or multiple sensors to enquire the raw data as the input of the robot. The sensor is encapsulated by a logical sensor model. Through data abstraction, a logical sensor provides data to downstream application in a uniformed interface without depending on hardware devices. In addition, the input/output agent provides interface to the communication layer. Based on the needs, pre-processing and further feature abstraction capability can be implemented in an input/output agent. Once the input information has been processed by the intelligence layer in the current context, a decision will be made and an execution command will be sent back to this layer for necessary actions.

3.2 Communication Layer

The communication layer provides a standard communication protocol to facilitate the information transmission between fusion unit and sensing modules. Currently, Transmission Control Protocol (TCP) structured message is used by the system. TCP protocol ensures that every message for intercommunication can be sent to destination without any possibility of message loss.

There are two types of messages: text and binary. Message type can be identified by a particular field in the message. In the mean time, every message also includes the following fields for clear and efficient communication: Time stamp, Sensor identifier, the command (purpose) of this message, and a list of parameters which is delimited by comma.

In the architectural design of communication layer, we promote system scalability and resolvability. The hub-and-spoke topology can be extended to support service oriented communication middleware such as SOAP and CORBA.

3.3 Intelligence Layer

The intelligence layer is the most important layer in the robotic platform. It integrates the information from a variety of diverse sources and performs further calculation and information fusion with various algorithms. This layer is able to perform higher level cognitive functions such as reasoning and action planning with the support of various intelligent engines. Once a decision has been made, response for different modalities can be generated and executed. As shown in Fig. 1, intelligence layer consists of event hub, multi-purpose script engine, intelligence fusion centre, a number of plugins of intelligence algorithms.

Event Hub. The event hub is an event-driven messaging engine for the effective message routing. Every message from different sources is passing through this hub. It provides a mechanism for the communication between remote agents and intelligence engines, or direct message passing from one intelligence engine to another engine. All

messages from the different sources are represented in a unified form and can be dispatched and handled in the same way. For the message source, besides the various input agent, a message could also come from an intelligence engine, XML command in script or a command issued by graphic user interface of the framework. The event sink could be an input agent, an intelligence engine, graphic user interface or script event handler. The conceptual diagram of the event hub is shown in Fig. 2.

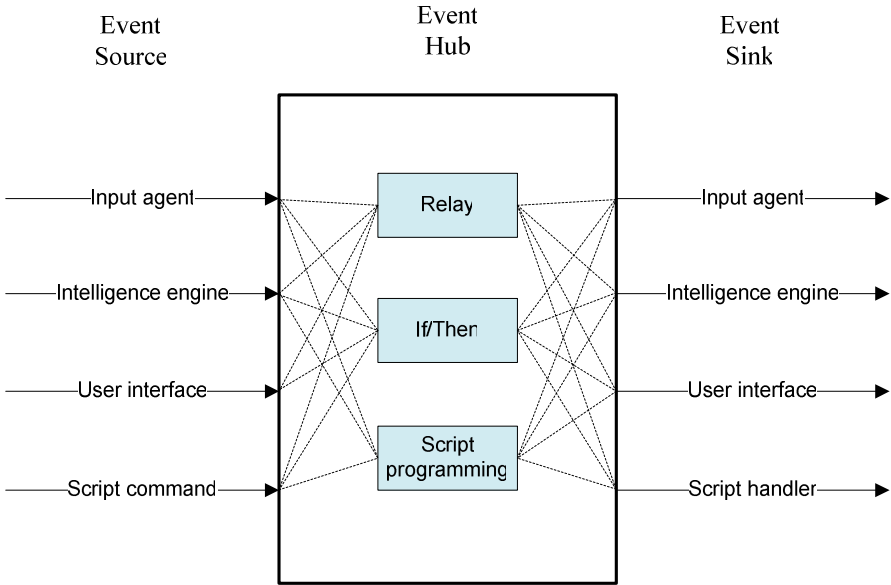


Fig. 2. Conceptual diagram of event hub

Functionally, the event hub is able to process all events in three ways as displayed in Fig.2. First is the direct message relaying. One message can be directly forward to one or multiple target receiving agents with change or without any change of parameters. Second is that the event is filtered by simple if/then rules, and then based on the filtering result to decide how to forward or generate an event. The last is event handling by a piece of XML script program. This is the most complicated and intelligent event processing. The script program will base on the receiving event, the current context and internal state of the robot to decide how to proceed with the current and new events.

Script Engine. To make a robotic platform viable for a variety of robotic applications, script language is always helpful for system configuration, message handling, non-time-critical process control, etc. In XRIA, a script engine is employed for different purposes, for instance, event hub programming, finite state machine (FSM), process logic control, XML programming for information processing, as well as the output control of actuators and various output modalities.

In selecting a modeling language for the proposed robotic platform, we determined that XML would be the most appropriate and promising language to use. In fact, XML is becoming a dominant scripting language for information storing, organization and business logic control because of its portability, extensibility, reusability and structured nature. In this framework, a multi-purpose XML script engine is developed to model and control the entire information acquiring, decision making and response generation.

Multi-purpose XML script engine is used to execute XML commands to fulfill following tasks:

- **Finite State Machine:** The engine itself can serve as FSM if there are state command and transition command in the XML script. Entry action, exit action, input action and transition action can be defined in XML script. In the mean time, within every state, all programming statements supported by the engine (assignment of variables, function calls, timers, etc) can be used.
- **Event Handler:** Different from FSM which only handles messages in current context, event handler is able to catch every event and process the message in global space. An event handler can be registered and un-registered any-time and anywhere. An un-registered handler will be in a suspended state, without processing any message.
- **Event Hub Programming:** The event hub is programmable with XML script as stated in last section shown in Fig. 2. The supported programmable functions include direct message relaying, if/then rule processing and script programming.
- **Control of intelligence fusion centre:** The script engine is able to control the intelligence fusion centre for dynamic loading and unloading of intelligence algorithm plug-ins, as well as the intelligence fusion logic such as the piped-line multi-step fusion process.
- **Decision Making:** After intelligence fusion, the fusion output is a high level abstraction or semantic representation of all sensory input in the present context. Decision making is a further step in this cognitive process to select a course of action among several alternatives. One way is to map the fusion result to the action space with the help of domain knowledge and rules.
- **Interpret and execute XML programming language:** Currently the engine supports most of the script programming capabilities such as scoped variables, if/else statement, arithmetic and logic operators, for loop, functions, timer, etc.

Intelligence Fusion Centre. The proposed framework allows the accommodation of various intelligence algorithms such as neural network, hidden Markov model and support vector machine, etc. All these algorithms can be packaged in various plug-ins and then plugged into the system through standard interface. Once an intelligence algorithm is plugged into the framework, it is able to receive all messages from different sensors or events from the framework. Intelligence fusion centre refers to the dynamic loading/unloading and indexing of various intelligence engines. In the mean time, it also manages the relationship between these engines. There exists scenario of

intelligence fusion which needs several engines to work in a pipeline manner. For easy management of fusion engines, every engine will be assigned with a type name based on its category and a unique identifier in its group of category.

Intelligence Engine Plug-in. XRIA is a framework which intends to host various intelligent algorithms so that the robot is able to possess required intelligence in accordance with the changing environment. To achieve the flexibility and extensibility, algorithms can be encapsulated in one or multiple plug-ins which can be loaded and activated on the fly.

The framework provides standard API for the integration and coordination of various intelligent algorithms by using object oriented and runtime late binding technologies. All plug-ins comply with a unified communication interface to ensure they can communicate with the event hub and talk to each other. For the communication interfaces which are abstracted from application-specific functionality, first they must be common to all fusion plug-ins. Second, the interface must meet the requirements of all fusion plug-ins for communication purpose. Followings are the most important interfaces for fusion algorithm plug-ins:

- **OnMessage** – This is the interface for plug-in to handle all coming messages from external sources. The message can come from a sensor, other intelligence plug-in, or the framework itself, which fires the message in XML script or through its graphic user interface.
- **FireEvent** – Interface to fire an event by the particular plug-in. This event can be captured by event hub and handled in XML script, or relayed to one or many other plug-ins.
- **SendMessage** – This is the interface to communicate with responding agents and intelligent sensors. This creates a way for intelligence plug-ins to directly communicate and control sensor modules, as well as output agents. For instance, intelligence plug-in can send a message to dialogue agent to speak a sentence through this interface.

XML Script. XML script contains message routing and generating commands, intelligence logic control commands, XML programming for simple message and information processing, as well as the output control of actuators and various output modalities.

A command object is instantiated in the XML document whenever a tag bearing the command name is encountered. For instance, a “send” command can be instantiate as follows:

```
<send module="Flash" command="msg_nbest_list">
  <param expr="staff" />
  <param expr="_PARAM1_" />
  <param expr="_PARAM2_" />
  <param expr="_PARAM3_" />
</send>
```

Through this command, a message will be sent to the agent, named “Flash” with information about speech recognition of staff name. All the information parameters here

have been saved into different variables. In the context of receiving message, all parameters can be directly accessed by system defined variables to improve the execution speed.

The XML script is power enough for simple programming and fusion control. It supports scoped variables, expressions, functions, if/else statement and loop control, timer and output commands. In addition, message and event handling commands are supported for communication, coordination and integration. For instance, send a message, pose a command, etc. Other miscellaneous functions and statements supported are “break”, “continue”, “random”, “sleep” etc.

Graphic User Interface. XRIA provides a graphic user interface to show the current status of a robot. The interface is configurable to certain extend based on the settings in a XML setting file. Its basic functions can be summarized as follows:

- Display server information – The platform runs as socket server and plug-in host. It displays server information such as IP address and socket port number, as well as all remote agents and their current status (online/offline). The agents, plug-ins and IP address to be bind to (if multiple IP addresses are available) can be configured in XML setting file.
- Display all messages and status of FSM – There is a console to display all receiving messages, sending messages, the current state of FSM and its transition. In addition, the console can be set to display limited debug information such as to track the change of variable value.
- Tool for firing events – Through the interface, an event can be fired in the similar way of script programming. For instance, dynamically load/unload a plug-in, send a message to remote agent, invoke a command to a particular plug-in, etc.

4 Implementation

4.1 Deployment on Robots

XRIA has been deployed on a number of robots in our laboratory, for instance, a robot named MIKA, who serves family member in home environment with fetch and carry operations activated by speech; Lucas, a robot endowed with capabilities to perform task relevant to information kiosk, butler, tele-presence, patrol and tele-operation; A receptionist robot OLIVIA, etc. All these robots come up with different configurations, perform different tasks and operate in a variety of environments. However, they are using the same robotic platform, XRIA. The implementation for all these robots is in a straightforward and timely fashion. What we have to focus on for different applications are functional level XML script and intelligence plug-in which can be easily developed based on the API provided by XRIA. If the algorithm for intelligence is not computational intensive, an alternative and easier way is to develop the algorithm in XML script directly. A neural network plug-in has been developed to classify human’s attention for receptionist OLIVIA from information such as face, eye gaze, lip movement, standing, pose and sound direction, etc.

4.2 Execution Performance

XRIA was developed in C++ and targeted at multiple platforms. Experiment was carried out with respect to the execution speed of XML engine because the system's response time very much relies on the XML engine performance due to its control to communication, FSM execution and management of intelligence fusion centre. The test was done on Dell Vostro PC: Intel Core 2 CPU @2.40GHz, 2.00GB of Ram running Windows XP. We looped the individual command for 10000 or million times depending on its speed. This loop test was repeated for 10 times and then the execution speed of commands was calculated as shown in Table 1.

Table 1. Execution performance of XML commands

Task	Time Taken (millisecond)
Script loading & compiling	78.150000
Assign variable	0.000030
Multiply two doubles	0.000066
For loop	0.013564
Function call with one parameter	0.008748
Send network message	0.024342
Print variable	0.396236

(* The XML script file is 332K in size with 57 FSM states and 10475 lines of code)

From table 1 we can see that XRIA is proficient in loading and compiling XML script. It is extremely fast in accessing variable, expression calculation and function call. For loop is a bit costly in time. The command "send" and "print" are affected by network traffic and GUI display speed.

5 Conclusion

A lightweight robotic platform, XRIA, has been developed and deployed on several robots in our laboratory. Differentiated itself from other state-of-the-art robotic platforms, XRIA provides a multi-purpose XML script engine for system communication programming, business logic control, FSM execution and decision making. In the mean time, XRIA employs a framework to enhance a robot's intelligence by various plug-ins which is endowed with required intelligent algorithms. Possible future enhancement for XRIA can be integrated visual XML programming environment, service oriented communication middleware and robot simulation framework.

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Socializing with Olivia, the Youngest Robot Receptionist Outside the Lab

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Abstract. In this paper we present the evaluation results of an exploratory study performed in an open environment with the robot receptionist Olivia. The main focus of the study was to analyze relationships between the robot's social skills and the perceived overall interaction quality, as well as to determine additional important interaction quality features with potential general validity. Our results show positive correlations between the investigated factors, as the ability to socialize with humans achieved the second highest correlation with the perceived interaction quality. One of the most relevant functional aspects for the interaction quality was found to be the ability to respond fast. Performance abilities, such as speech or object recognition were, surprisingly, considered less important. The voice pleasantness was regarded as one of the most important non-functional aspects being ranked higher than a nice physical appearance.

Keywords: social robots, quantitative evaluation, non-laboratory conditions.

1 Introduction

Since technology advances in engineering and computer science of the last decade brought the use of robots outside their traditional industrial 'playground' there has been a growing interest in designing socially competent robots for entertainment [1], educational purposes [2], healthcare assistance [3], as museum tour-guides [4], or receptionists [5,6].

As more and more social robots become available to the general public, there is an increasing trend to carry out experiments and evaluation studies in real-environment settings where the robots are meant to function. A number of social robotic projects have performed such studies with different research goals: for example Robovie [7], an interactive humanoid robot was used to explore friendship relationships between the robot and elementary school children; the robot receptionist Valerie [5] and its updated version Tank [6] were deployed to investigate long-term relationships with humans. Studies performed with the robot Pearl [3] investigated how the robot's social skills helped to improve task performance in the elderly. Minerva [4], a museum tour guide, was used to explore short-term spontaneous interactions with crowds of people.

In this paper we present the evaluation results of an exploratory study performed with the robot receptionist Olivia during the annual two-day exhibition *TechFest*, organized in October 2009 at I²R, Fusionopolis (Singapore). Olivia is the 4th service robot model developed by the A*STAR robotic team from I²R (Singapore). The robot's role was not only to act as a receptionist but also to represent the institution as a kind of mascot.

Unlike the robots presented in the other studies, Olivia has the embodiment and behavior of a child. Olivia uses her childish charm to draw adults' attention so that they will interact with her. Since it has been proven that humans often treat artificial entities as though they were real [8] we hoped that Olivia's cute behavior would induce the sympathy people usually feel for young children and consequently, her overall abilities would be more positively assessed. Thus, the main goal of this research paper is, besides exploring the social relationship between humans and Olivia, to determine how the robot's social skills relate to the overall interaction quality as perceived by users. Furthermore, we investigate how people assign different ranked priorities to several functional and non-functional conversation aspects according to their importance for the interaction quality with the robot. With our study we expect to gain insights not only into interaction with Olivia, but also into the general quality features relevant to human-robot interactions.

2 Methods

2.1 Experimental Set-Up

Many human-robot evaluations presented in the social robotic literature were carried out under controlled lab conditions, where the human social 'landscape' was artificially re-constructed. These studies are especially useful for experiments aiming to determine the effects achieved through different variable manipulations. On the other hand, such experiments do not provide insights on how people would interact with the robot in spontaneous real-life situations, nor are the testing conditions comparable, i.e. systems that work well in the lab are often less successful in noisier field environments. Hence, it is necessary to evaluate human-robot interactions as socio-culturally constituted activities outside the laboratory [9].

In our study the robot receptionist Olivia interacted with human visitors in an uncontrolled real-life environment. The robot's tasks were to inform and entertain the *Techfest* visitors by presenting information about building amenities, daily horoscopes and by playing a simple game consisting of recognizing and tracking different objects.

Attached to the robot was a touch screen where additional information cues were displayed (see figure 1). Visitors could communicate with Olivia using speech or the touch screen. The topics and the games were randomly initiated by the robot: being equipped with visual-recognition capabilities Olivia was able to detect a person standing in front of her and accordingly, could initiate the conversation naturally. A conversation with Olivia typically lasted around 3-4 minutes. Olivia was accompanied by a human assistant standing at 2-3 meters distance. Visitors were free to talk with the assistant and ask questions about the robot, if they wished to. After interacting with Olivia visitors were kindly asked to fill in an evaluation questionnaire.

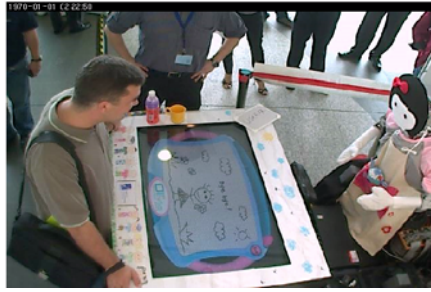


Fig. 1. Visitor interacting with the robot

2.2 Designing a Robot with Human Social Behavior

Engaging socially in verbal interactions, as simple as it might appear for humans, is in fact a highly complex process, requiring a synchronized interplay of affective, conversational and personality related behavioral cues. Fong et al. [10] translated these cues into a list of design characteristics that robots aiming to exhibit human social behavior should possess. These characteristics are: 1. express and/or perceive emotions; 2. communicate with high-levels dialogues; 3. learn/recognize models of other agents; 4. use natural cues (gaze, gesture, etc); 5. exhibit a distinctive personality or character. All these characteristics – except for 3rd - were implemented in Olivia’s behavior design.

One of Olivia’s most distinctive features is her role: she represents a robot mascot that looks and talks like a child; dressed up in a cute pink skirt and wearing a red ‘hair’ ribbon Olivia speaks to visitors with the typical charm of a very young person. Since her ‘job’ as receptionist and entertainer requires interacting with many people Olivia’s personality was designed to be extrovert - as shown in the literature [11], extroverted individuals have enhanced social skills that allow them to communicate easily with others.

Olivia’s personality profile was derived from Eysenck’s [12] personality extrovert model. The model contains 7 traits such as being outgoing, talkative, lively, carefree (e.g. cheerful), responsive, easygoing (e.g. cooperative), leadership (e.g. dominant). These personality traits were implemented as follows:

1) Outgoing: Olivia’s outgoingness manifests in a very friendly way of approaching people: always ready to engage in a conversation the robot usually makes the first ‘move’, greeting people passing by and asking them to spend time with her (see table 1).

2) Talkative: Olivia loves to talk and often adds a very personal touch to her discourse: visitors are informed not only about building amenities or horoscopes but also about Olivia’s family members living in the building, about her preference for *kaya* toast or her passion for swimming. Because talkative people often use gestures to communicate, Olivia’s statements are accompanied by head, arm and body movements meant to emphasize the intended message: for example, the robot uses her arm

to point at relevant information cues on the screen or to show direction, shakes her head to express dizziness, waves her hand to greet people or rotates her arms to demonstrate how she swims.

3) Lively and cheerful: Olivia’s speech and gestures unveil highly emotional features that leave the impression of a cheerful character with a highly animated personality: using a colorful intonation and many interjections Olivia shows surprise (“wow”), when a visitor’s horoscope sign matches the one of her ‘mommy’, fear (“oh”) when she meets a dangerous Scorpio person or joy (“hey”) when she comes across a Cancer man as she likes the “yummy” taste of “chili crabs”; she yells for joy when she finds an object during the visual recognition game, ‘yawns’ to show boredom or complains of getting ‘dizzy’ when the tracking game lasts too long; in the end she gives visitors a cute onomatopoeic good-bye kiss.

4) Responsive and cooperative: Olivia’s responsiveness and cooperativeness is expressed at three different levels: at the dialogue structure level, semantic level and gestural level. Through an implicit feed-back strategy (“Oh I see, you are a Leo!”) the visitors are directly addressed by the robot and confronted with the internal processing state of their inquiry. On the semantic level the robot shows her interests in people’s horoscopes revealing often positive characteristics: Taurus are flattered for being big and strong and Virgos for being intelligent people. Also at the gestural level Olivia shows her readiness to help by leaning her upper body and head towards the touch screen in an attempt to look for corresponding answer images that she can point at.

5) Dominant: Since our experiment was carried out in uncontrolled environment settings there is a need to guide the visitors in order to maintain a smooth interaction. Thus, this personality trait derived from the leadership characteristics was added to Olivia’s personality model. Olivia’s dominance is expressed on the dialogue structure level - the conversations is initiated, lead and ended by the robot - and on the semantic level - the robot uses the first person to refer to herself often displaying an assertive verbal behavior (e.g. “I like *kaya* toast!”).

Table 1. Excerpt from two conversations with Olivia

Amenities dialogue	Game dialogue
<p>Olivia: Hi (<i>waving hand</i>)! I am Olivia! Nice to meet you! User: Nice to meet you too! Olivia: Would you spend some time with me? User: Sure! Olivia: Hmhm (<i>clearing her ‘throat’</i>)... I know a lot about amenities here (<i>makes a round movement with the arm showing the amenities depicted on the screen</i>). Tell me, which one you like to know more? User: I would like to know more about “Fitness First.” Olivia: Hm ... my daddy works out at “Fitness First”, located at level 23 (<i>points on the screen where the fitness center details are displayed</i>).</p>	<p>Olivia: Now, let’s play a game! User: Ok, what game? Olivia: Hmhm (<i>clearing her ‘throat’</i>)... pick up my toy (<i>points to her book left on the screen and looks up at the visitor</i>) and move it slowly in front of me, as I follow the motion. User: (<i>moves the book too fast</i>) Olivia: Hey! It’s too fast! I can’t catch up with you! User: (<i>moves the book slowly</i>) Olivia: It is fun! (<i>moves her head following the book; after sometime starts ‘yawing’ and pushes her upper-body closer to the book; after sometime starts shaking her head and brings back her upper-body</i>) I am getting dizzy! Let’s stop here! User: (<i>puts the book down</i>) Olivia: Muac (<i>kiss sound</i>)! Thank you for playing with me and have a nice day (<i>waving hand</i>)!</p>

2.3 Technical Features

Olivia is approximately 152 kg and 1.6 m tall. The robot has 13 degrees of freedom in total: head (3 degrees), body (2 degrees) and hands (2x4 degrees). It is built on a PowerBot base mobile platform and equipped with several hardware/mechanical components, including actuators (servomotor, harmonic gear system, drive unit and harmonic drive servo actuators) a laser (Hokoyu URG-04LX), cameras (Bumblebee[®]2 and DVN1501 mono camera), microphones and speakers. The robot has several independent software modules for controlling and executing several functions: a motion control (MC), a dialog management system (DMS) and a vision understanding (VU). The MC module employs advance motion control algorithms, such as nonlinear task space control and joint space control to control the robot's movements. The DMS module utilizes the Loquendo 7.52 text-to-speech (TTS) software to generate a female, child like voice with an American English accent (timbre & pitch=70, speech rate=30, volume=50). The TTS enables the use of several emotion cues, such as hesitation sounds, coughs, yawning, etc. To increase the speech recognition accuracy the DMS' acoustic model was trained with 13.5 hours of read speech data, collected from 40 English non-native speaker subjects (mostly male). For the data collection a 200 word vocabulary was used; additional word entries related to the two main conversation topics (building amenities and horoscopes) were included (50 words per topic). The VU module deploys a multi-model fusion maximum likelihood method by integrating four different approaches: stereo-based human detection, HOG- based human detection, color-based tracking, and motion estimation for human detection and tracking. All software modules run two PC boards: one Intel Corei7 (2.8 GHz) and one Atom processor (1.2GHz).

2.4 Questionnaire Design

Since we are interested in the relationship between the robot's social skills and the perceived overall interaction quality, it is important to find adequate ways to measure them. Additionally, we are interested in finding the most relevant conversational aspects contributing to a better interaction assessment.

A tool widely used in behavioral research for social skills evaluation was developed by Gresham and Elliott [13]. The tool is meant to assess human social skills along five categories: cooperation, assertion, empathy, self-control and responsibility. These categories were found to match social abilities aspects involved in human-robot interaction [14] being related to the design characteristics presented by Fong et. al [10]. Translated to Olivia, these abilities, partly overlap with her extrovert personality characteristics and are expressed in the following way: cooperation manifests in her readiness to help others by sharing information in a highly sociable manner, referring to her 'own' experiences and using gestures to enhance explanations. Assertiveness relates to Olivia's extrovert personality, as she initiates the conversation, introduces herself and shows openly her preferences and dislikes. Olivia expresses empathy through emotional, verbal interjection. For self-control and responsibility no direct related aspects were found. Since many authors [15] suggested that humor has an important role in interpersonal relationships, being a social skill in itself, we included it

in our investigations. Olivia's humor is, however expressed only through a personalization effect: the robot often refers to itself as it would be human, creating a hilarious impression (see table 1). Consequently, we built up a *social skills* subscale with 5 items: the ability to socialize (i.e. ability to be friendly), to use natural gestures, to express emotion, personality and humor.

To evaluate the interaction quality we used the SASSI [16] questionnaire as inspiration. The questionnaire was developed to evaluate the usability of uni-modal speech-based interfaces and it addresses five different dimensions: response accuracy, likeability, cognitive demand, annoyance, habitability and speed. Because evaluating the interaction quality with a multimodal interface differs somewhat from assessing the usability (fit-for-use) of a uni-modal system we needed to modify the questionnaire to suit our purpose. Accordingly, we retained only items corresponding to the interaction features and their effects on users' mood; additionally we replaced the accuracy dimension with a more precise category referring to the robot's multimodal performance and we semantically re-grouped the items in two factor subscales: *interaction features* and *user feelings*. The interaction features subscale contained 8 items: interaction easiness, level of concentration, response speed, usefulness, flexibility, speech/object recognition and object tracking. The user feelings subscale includes only 3 items: enjoyment, calm and comfort; the comfort was not listed in the SASSI questionnaire, but it is often mentioned in the literature along with user enjoyment as contributing to the overall interaction quality perception [17].

According to Hassenzahl et al. [18], the user evaluation of a system is influenced by its pragmatic and hedonic quality. Applied to conversational interactions, pragmatic quality would refer to *functional aspects* determining how well a certain communicative goal is achieved, while hedonic quality would relate to *non-functional aspects* indicating how much the user enjoyed the interaction. Thus, we selected from the SASSI questionnaire and other relevant evaluation studies concerning multimodal conversational interaction [17] a total of 16 items, applicable to Olivia and social robots in general. 7 items were related to functional aspects, such as interaction speed, content relevance, clarity of answers, speech/visual recognition accuracy, system transparency and easy recovery from errors. The other 9 items were concerned with non-functional aspects, such as voice and appearance pleasantness, friendliness, politeness, humor, emotion display, gestures and mimic, display of human-like physical characteristic (gender and age).

The questionnaire was divided in two parts. In the first part visitors scored the subscale items using a 5-point Likert scale with 'strongly agree/disagree' as endpoints. In the second part they ranked the functional and non-functional aspects according to their importance for the interaction quality. A 7-point scale with 'not important at all/extremely important' as endpoints was used for the ranking in order to ensure more differentiated results. The questionnaire ended with a general question about the perceived *overall interaction quality*.

3 Results and Discussions

From 121 visitors who interacted with Olivia 88 filled in the questionnaire. 67.8% were male and 32.2% were female. 73.3% were of Chinese origin, 14.4% Indian, 12.1% other nationalities. The majority (71.1%) had an IT & engineering background,

the rest sharing a background in business (13.3%), arts & humanities (5.6%) and other areas (9.9%). 66.7% were aged between 26-40 years, 20% between 18-25 years and 13.30% were above 41 years. More than half of the visitors (54.5%) were Master or Ph.D. holders; 34% had a Bachelor degree and 11.1% held other diploma degrees. Probably, due to a technical educational background a relatively high percentage (47.2%) had seen or read about robots and some visitors (24.5%) had even interacted with them; also other few (6.7%) had expertise in robot design & development. 24.5% had no knowledge of robots. A lower percentage of visitors (38%) had used speech recognition devices – mostly as input modality for mobile phones, video games, cameras, dictation systems; a very small number of visitors (3%) used the Microsoft SDK tool to build speech recognition applications; 61.10% of the visitors had no knowledge about speech recognition devices.

Next, we checked the internal consistency of the proposed subscales, as well as the cumulated negative ('disagree' + 'strongly disagree'), positive ('agree' + 'strongly agree') and neutral scores achieved by each subscale item¹. The reason behind listing the cumulated values lies in understanding the general item evaluation tendency. Subscales with $\alpha > .600$, item total correlations $r > .300$ and a reduced number of items (< 10) are generally considered as acceptable [19].

Table 2. Robot social abilities subscale and item cumulated score values

Robot's social skills	Items	Item-total correlation r	C _{neg}	Neutral	C _{pos}
N of items: 5 Cronbach $\alpha = .789$	Socialize	.524	5.70%	42.00%	52.30%
	Nat. gestures	.536	15.90%	43.20%	40.90%
	Personality	.646	17.00%	48.90%	34.10%
	Emotions	.621	26.10%	39.80%	34.10%
	Humor	.499	15.90%	52.30%	31.80%

The analysis of the robot's social skills subscale (see table 2) revealed a high internal consistency ($\alpha = .789$). According to a Friedman test, significant differences between the items were found ($\chi^2(4)=26.671, p=.000$). Thus, we conducted a post-hoc analysis with a Wilcoxon Signed-Rank test (W_+) applying a Bonferroni correction (BC) for multiple comparisons; a new p-value was set at $p < .012$. The test showed that the ability to socialize was significantly higher scored than all others subscale items ($p=.000$), except for the ability to express natural gestures ($p=.016$). The lowest rated item seems to be the ability to express emotion, however no significant difference with respect to the other items was found. All subscale items, except for the ability to socialize show high frequency distributions in the neutral category. This means that Olivia's social skills are acceptable, as she can 'socialize' but most of the features need improvements. Especially the ability to express emotions - a key item with the second highest subscale correlation ($r=.621$), but also highest negative ratings (26.10%) - should be given special attention in the future. The lack of mimicry on Olivia's face, most probably might have lowered the rating, as humans typically expect emotion expression to appear synchronized at both voice and face level.

¹ Since the data is not normally distributed we do not report the mean.

Table 3. User feelings subscale and item cumulated score values

User feelings	Items	Item-total correlation r	C _{neg}	Neutral	C _{pos}
N of items: 3 Cronbach $\alpha = .696$	Comfort	.433	10.20%	36.40%	53.40%
	Enjoyment	.551	6.80%	29.50%	63.60%
	Calm	.574	2.30%	21.60%	76.10%

The reliability analysis performed on the user feelings subscale proved an internal consistency of $\alpha = .696$ (see table 3). Since all items showed relatively good scores we assume the majority of the visitors felt comfortable and calm while interacting with the robot, enjoying the conversation.

The interaction features subscale showed an internal consistency of $\alpha = 0.645$ (see table 4). Two items -attention level required and interaction flexibility- were removed because of low correlations with all scale items and with the overall interaction quality ($r = .087$, and respectively $r = -.174$, $p = n.s.$).

Table 4. Interaction feature subscale and item cumulated score values

Interaction features	Items	Item-total correlation r	C _{neg}	Neutral	C _{pos}
N of items: 6 Cronbach $\alpha = .645$	Easiness	.438	13.60%	40.90%	45.50%
	Interaction speed	.331	27.20%	44.30%	28.40%
	Usefulness	.361	1.10%	34.10%	64.80%
	Speech recognition	.390	1.10%	22.70%	76.20%
	Object recognition	.385	4.50%	23.90%	71.60%
	Object tracking	.329	5.70%	37.50%	56.80%
Removed parameters	Items	Item-total Correlation r	C_{neg}	Neutral	C_{pos}
N of items: 2 Cronbach α (if included) = .485	Attention level required	.091	4.50%	15.90%	79.50%
	Flexibility	-.198	30.60%	37.50%	31.80%

A post-hoc analysis (W_+ , BC, new $p < .012$) performed after the Friedman test ($\chi^2(5) = 86.336$, $p = .000$) showed significant differences between the interaction speed and easiness on one side and all the other items, on the other side ($p = .000$). Also, significant differences were found between speech recognition and object tracking capabilities ($p = .000$).

The response slowness was mostly caused by speech² and visual recognition difficulties in respectively, 54.40% and 28% of the cases; since no feed-back or error recovery strategies were implemented, i.e. no reaction came when the recognition score was below a certain threshold, the visitors were left with the impression the robot's response was slow. Table 5 presents an overview of response latencies³ for speech and object recognition, as well as for visitors' tolerance level⁴ to speech response latencies. The robot's response latency in speech recognition error-free cases

² The speech recognition problems were caused by a noisy environment (92.80%), wrong pronunciations (4.8%) and other technical issues (2.4%).

³ Response latency refers to the time elapsed between last user input and robot's response.

⁴ The tolerance level refers to the time elapsed until a user re-prompts her input when no response is given.

was on average 2.51sec, a value still far behind that found in human face-to-face conversation - 0.97 sec, [20].

In cases with speech recognition errors response latencies were higher, lasting on average 3.18 sec; in such cases, total response time⁵ could achieve extreme (but luckily infrequent) values of even 45 sec. Compared with human face-to-face conversations, where a delay of more than 2-3 seconds in providing a response was found to cause discomfort [21] it becomes clear that such response latencies are unacceptable. Interestingly, the delay value mentioned above corresponds roughly to the tolerance level of 3.74 sec measured in our study. Thus, we would expect high correlations between speech recognition errors and the speed scores. But surprisingly, this was not the case: the speech recognition and the interaction speed have a correlation coefficient of only $r=.279$. A further detailed analysis revealed the speech recognition performance correlates with the speed scores in only 30% of the cases: many visitors (44.30%) scored the interaction speed as being neutral - neither fast, nor slow, even by high response latencies (23 up to 45 sec.) or by relatively low latencies (1.5-2 sec.). This leads to the following three remarks. Firstly, an average response latency of 2.51 sec is too high. Secondly, the question referring to speech recognition abilities (“The robot was able to recognize my speech”) should have been formulated more accurately (e.g. “The robot’s ability to recognize my speech was very good”); since Olivia always provided a response, even after long response delays, it means she was ‘able’ to recognize speech; therefore, the question might have generated misleading responses. Thirdly, many visitors tended to avoid negative scores choosing instead neutral ratings; this tendency of scoring more positively in order to please the interviewer or to be helpful was also observed by other studies [22].

Table 5. Robot’s speech and visual average response latencies in seconds

Response latency	Mean	Median	Modus	Min.	Maxi.
ASR error free	2.51	2	2	0.75	7
ASR with errors	3.18	3	2	1	15.50
Total time until response-ASR errors	14.96	11.25	6	4	45
Visual recog. error free	1.77	1	1	0.25	11
Visual recog. with errors	13.52	12	11	4	27
Tolerance level	3.74	3.31	3	2	9.33

Table 6. Overall interaction quality scale with cumulated score values

Scale	C _{neg*}	Neutral	C _{pos}
Overall interaction quality	2.00%	30.7%	63.6%

Similar rating behaviors were observed between speech recognition performance and the scores obtain in overall interaction quality (see table 6): the presence or absence of speech recognition errors corresponds to a negative/positive overall quality assessment in only 34.66% of the cases; visitors gave more neutral scores, even if the robot obviously failed to recognize their speech and her response had long delays. We

⁵ The total response time refers to time measured between first user input and robot’s response.

also compared the ratings for enjoyment in cases with speech recognition error and found that in 60% of the cases nevertheless, the visitors gave high ratings. Looking at the enjoyment correlations outside its own subscale we found the highest correlations with interaction easiness ($r=.442$), ability to socialize ($r=.436$) and overall quality ($r=.418$). Thus, the visitors' tendency towards more positive ratings as observed in [22] might have an additional, complementary explanation: people might have rated the interaction features and overall quality better because they experienced an enjoyable (and not particularly difficult) interaction with a sociable robot.

Finally, we analyzed the correlation between the subscales and the perceived overall quality (see table 7). All subscales correlate significantly with the overall interaction quality, whereas the interaction features have the highest correlation coefficient ($r=.600$). The robot's social skills have a lower correlation coefficient ($r=.444$) but to some extent higher as compared with the user feelings. Additionally, we checked the correlations between the overall interaction quality and each subscale item to detect the highest correlations; we found that the interaction easiness ($r=.490$), the ability to socialize ($r=.435$), the enjoyment ($r=.418$) and usefulness ($r=.409$) had the highest correlations ($>.400$) with the overall interaction quality. On the other hand, the interaction features were significantly better evaluated than the robot's social skills (W_+ , $p=.000$).

Table 7. Overall quality scale with cumulated ratings

Subscales / Overall Quality	Min.	Max.	Mean	Std. deviation	Correlation with overall quality r
Robot social skills	2.00	5.00	3.2409	.55183	.444**
User feelings	2.00	5.00	3.6629	.55936	.435**
Interaction features	2.67	4.83	3.5568	.43468	.600**
Overall scale	2.64	4.79	3.4156	.37021	.589**
Overall quality	2.33	5.00	3.5083	.58880	1.000

** $p < 0.01$

Next, we analyzed the priorities ranks visitors assigned to different functional and non-functional aspects that might be involved in the face-to-face conversation with a robot (see table 8). Despite a non-normal data distribution we chose the mean as sole option to build a differentiation order. However, the rank order can be validated by only applying a non-parametric significance test. The mean scores show a demarcation line between the functional (1-7) and non-functional (8-16) aspects. The functional aspects were on average significantly higher ranked than the non-functional (W_+ , $p=.000$). This finding is not surprising, since functional aspects are, from a pragmatic point of view, more important than non-functional aspects, e.g. the robot's nice appearance would not replace its poorly working speech recognition. Nevertheless, this does not mean non-functional aspects are unimportant. In fact, many studies proved the benefits of non-functional aspects such as emotion displaying, gesture and mimicry for the robot's social acceptance or human-like skills [10].

The result of the post-hoc analysis (W_+ , BC, new $p < .008$) performed after the Friedman test ($\chi^2(6)=18.38$, $p=.005$) revealed that the interaction speed was statistically higher ranked than the error-free speech/object recognition ($p=.006/.007$); this means that users could be more tolerant to errors, but less understanding if they have

to wait too. No significant rank differences were found between the other aspects, except for the system transparency whose mean was significantly lower than those of the interaction speed ($p=.005$).

Among the non-functional aspects statistically significant differences could be found ($\chi^2(8)=175.696, p=.005$). The post-hoc test ($W_+, BC, new p <.006$) showed that the pleasant voice, friendly behavior and politeness were significantly higher ranked than the humor and the gender/age displaying. In fact, both gender/age displaying were included on the aspects list because of their relative importance in verbal addressing in Asian cultures; however, they achieved the lowest statistically significant ranking of all aspects ($p=.000$). Interestingly, a pleasant voice achieved a statistically significant higher mean than a nice physical appearance ($W_+, p=.005$). This result could be explained as follows: even if the visual impression of the robot would impact visitors in the first place, its voice might play a more important role in the interaction, since it conveys the required information.

Table 8. Mean scores and significance levels for functional and non-functional face-to-face conversational aspects

No.	Category	Mean	Significance level relative to the other item rank ⁶	
1	Interaction speed	5.83	*=5,6,7; ***=8-16	ns= 2-4
2	Easy recovery from errors	5.80	***=8-16;	ns=1,3,4-7
3	Clarity of answers	5.77	***=8-16;	ns=1,2,4-7
4	Delivering relevant information	5.72	***=8-16;	ns= 1-3, 5-7
5	Error free speech recognition	5.67	*=1; ***=9-16;	ns=2-4,6-8
6	Error free object recognition	5.61	*=1; ***=9-16	ns=2-5, 7,8
7	System transparency	5.52	*=1; ***=10-16;	ns=2-6, 8, 9
TOTAL	FUNCTIONAL ASPECTS	5.70	*** TOTAL NON FUNCTIONAL	
8	Pleasant voice	5.26	**=1-4,12, 14-16;	ns=5-7,9-11,13
9	Friendly behavior	5.22	**=1-6,14-16;	ns=7,8,10-13
10	Gestures and mimic	5.01	**=1-7,15,16;	ns=8, 9,11-14
11	Polite way of talking	5.01	**=1-7,14-16;	ns=8-10,12,13
12	Nice physical appearance	4.95	**=1-8,15,16;	ns=9-11,13,14
13	Emotion displaying	4.92	**=1-7,15,16;	ns=8-12,14
14	Humorous way of talking	4.72	**=1-9,11,15,16;	ns=10,12,13
15	Gender displaying	4.10	**= 1-14, 16	ns= none
16	Age displaying	3.66	**=1-16	ns= none
TOTAL	NON-FUNCTIONAL ASPECTS	4.80	*** TOTAL FUNCTIONAL	

4 Conclusions

In this study we analyzed relationships between a robot's social skills, interaction features and user feelings on one side, and the perceived overall interaction quality, on the other side. Our results showed significant correlations between these three factors and the perceived overall quality, the interaction features showing the highest correlation. We would have expected a stronger relationship between the robot's social skills and the perceived overall interaction quality. Nevertheless, the ability to socialize seems to play an important role, being the second most correlated item with both enjoyment and overall interaction quality.

⁶ *** significant at: $p < .005$ (9 comparisons), ** at $p < .006$ (8 comparisons), * at $p < .008$ (6 comparisons); 'ns' stands for not significant.

The robot's speech recognition performance was better ranked than the error logs and total competition time would have predicted. This might be explained, partly by the question formulation bias, partly by a general human tendency to give more positive ratings and partly because the visitors enjoyed the interaction despite errors and long response delays.

The conversational aspects ranking brought us important information that can be used to improve the robot design and set priority decisions: for example, it seems that visitors were more tolerant to errors than to long response latencies. A pleasant voice seems to be more important than a nice physical appearance while humor and gender/age displaying appear to be less important conversational aspects for the interaction quality.

Both, aspects ranking and correlations obtained from the items' evaluation suggest that the overall interaction quality relates more to the robot's ability to lead the interaction (response speed, clarity of answers, interaction easiness) and to appear agreeable (friendly, i.e. sociable, having a pleasant voice), than to its performance accuracy, in terms of speech and object recognition/tracking.

In the future Olivia's dialogue design would incorporate an error-handling strategy to reduce the robot's response perceptions as being slow. Also, help options and a better system transparency would be integrated to enhance the interaction easiness. Further, adding mimicry to Olivia's face to show emotions, improving her gesture to becoming more natural and making the dialogue script more amusing might increase the robot's perceived ability to socialize. Our results are originated from an exploratory study and therefore, cannot prove causal relationships between the analyzed items. Nevertheless, the study revealed significant item correlations that can be used to improve the current robot design. Their significant impact could be examined in future contrastive laboratory conditions to find statistical evidence.

Acknowledgments

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Minimal Set of Recognizable Gestures for a 10 DOF Anthropomorphic Robot

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Abstract. Gestures play an important role in the communication of social robots. This paper presents an approach to simplify the upper body of the robot, proposing a method resulting in a smaller and cost-effective way of building robots which can perform gestures that are recognizable to humans. A reduced robot model of 10 Degrees of Freedom (DOF) is investigated and the human gestures are mapped directly onto the robots. Results from our user study show that the decrease in DOF does not critically affect human-like gesture motions to significantly affect the perceptions by the human observer. Specifically, some gestures have shown that participants make no mistake in interpreting the robot gestures, suggesting the possibility of its implementation on pre-programmed motion on robotic toys.

1 Introduction

Social robots are coming of age. As they are slowly emerging to co-exist with us in our own homes, we must try to understand how we can better communicate with them. Research over the decade has shown that anthropomorphic robots lead users to expect human-like behavior, further boosting the need for robots to communicate in a human-like manner [1]. To achieve human-like communication on a social robot, human-human communication has to be understood. Moll [2, 3] mentioned that in human-human collaboration, cooperative gestures play a key role in helping communicate intent, instruct, lead and build rapport. Referring to Mehrabian's 7%-38%-55% rule [4], which explains how each of the three elements in face-to-face communication affects one's liking for the other, non-verbal behaviors dominates 93% communications in human-human interaction, and body language particularly accounts for 55%.

It has also been shown that humans are typically well-adept at inferring another's intentions and emotions in order to spontaneously coordinate to achieve shared goals. Riek [5] elaborates that this ability is rapid and comes naturally to us when we are interacting with other humans who communicate with us through gestures. Yet, it is unclear how the relationship will be when interacting with humanoids. In addition, the social cues of future robot products enable people to accept them more naturally without rejection and the design cues could be gesture, eye gaze, speech, sound, motion, proximity, and personality [6]. Fong and his colleagues [7] have emphasized that

using gestures is a key design feature for robot communication while Cassel and colleagues [8] demonstrated that when words and gestures were discordant in human computer interaction, gestures had more meaning for people compared to words.

The fundamental robotics work to tackle imitation was focused on assembly task-learning from observation [9]. Moreover, typical series of arm trajectories were recorded using a manipulandum, with the advantage of measuring directly the joint torques. Data are then analyzed to remove inconsistencies and key features of the movement are extracted. This was implemented in this paper as the gestures have been preset and the main focus lies on the gesture interpretation.

A large number of Degrees of Freedom (DOF) on a robot causes it to be huge and bulky, rendering difficulties in practical implementation. For example, Billard's research [9] investigated robot imitation with 11 DOFs. A conventional Lynx-6 robot arm consists of 6 DOF, amounting up to 14 DOFs in this case [10]. Other humanoid robot arms also range from 6 DOFs to 8 DOFs [11-13]. More flexibility on the robotic arms requires an increase in the DOF but contributes to larger overall DOFs and thus impeding practicality.

In this paper, investigations were carried out on an anthropomorphic robot with 10 DOF to examine whether the human observer can identify gestures made by the robot. Li [14] pointed out that there are five broad categories of gestures, namely irrelevant and manipulative gestures, side effect of expressive behavior, symbolic gestures, interactional gestures and referential or pointing gestures. The primary focus of this paper will be on symbolic gestures, whereby the semantic content of the communication gesture is related to the intended meaning of the gesturer, as it allows the meaning of the communication to be explicitly stated.

Our work aims to work on the above approaches by investigating the human response for a robot with even reduced DOF. The endeavor is to further simplify the mechanics of the robot, without critically affecting the human-like behavior. Our work packages a more compact and cost effective robot, allowing for a larger variety of usage in various industries particularly for the toy industry. Section 2 describes the materials, and the experimental procedure. Section 3 presents the results and discussion. Finally, Section 4 concludes the study.

2 Experiment

2.1 Materials and Method

A re-configured anthropomorphic robot (Scout², Dr. Robot, Ottawa Canada) was used for the experiment. It had 2 DOF of the neck, 2 DOF in each shoulder, 1 DOF on each elbow and 1 DOF on each wrist. 25 gestures ranging from simple gestures requiring only 1 DOF such as nodding, to more complex gestures such as conducting and hugging were selected. Due to the nature of the DOFs, the gestures only involved the head and the arms. These body parts are principally controlled by our software developed through Microsoft Robotics Developer Studio and Microsoft Visual Studio. The software allows for the execution of our preset gestures that has been mapped onto the social robot.

In the mapping of the preset human gestures to the robot, considerations were placed on factors such as the timings of the gestures. The angles were set to ensure that the gesture look natural. The speed of the gestures was controlled by the number of via points introduced in the execution of each gesture. This also contributed to a smoother gesture flow. Simpler gestures had at least 50 via points whereas complex gestures had up to 200 via points. These points were then sent at intervals of 25ms to the servo controller, which would then command the servo motors to move to the desired location.

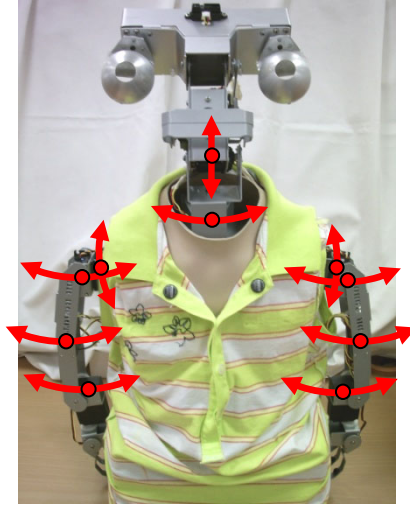


Fig. 1. Robot with the location of DOFs

2.2 Procedure

Participants were recruited through email advertisements and by word-of-mouth. They were told they would be taking part in a video-based experiment involving robot gestures. A total of 20 participants participated in this experiment and no one had prior experience in dealing with social robots. This was to best simulate the response of a typical individual and not let their knowledge of robots bias their judgment. Their ages range from 18 to 24 and all were undergraduate students.

As the user study involved individual interpretations of participants, each experiment could only be conducted on one participant at a time. The experiment was conducted in a room that was well-lit and the contrast of the screen was kept constant. Throughout the experimental study, the playback of the recorded video would be displayed on a monitor screen with full brightness. Upon arrival, the participant would be provided with a sheet of questionnaire which included a brief introduction on the overall flow of the experiment and a blank in front of each gesture's number for the participants to fill in with their interpreted gesture. It should be noted that the gestures are numbered in the order they are shown in videos. The participant would then begin the first section of the experiment by viewing a series of videos of human gestures.

This involved running pre-recorded videos of 25 human gestures to the participants. In the preparation of this video, a human demonstrator would carry out each gesture individually, which would be recorded. This was to minimize errors, such as movement variability, due to human factors such as fatigue. The demonstrator had good health records without any physical disabilities. To prevent distractions due to motions from other parts of the body, the demonstrator would be sitting on a chair while executing the gestures. This was to restrict and limit any movements in the lower part of the body, thereby focusing the attention on the head and arms only. An example of a hugging human gesture video in still frames could be seen in Fig 2a.

After the participant watched each human gesture video, he would record his interpretation of gesture he observed on the questionnaire provided. Between one gesture and another, a black transition screen, which lasted for 5 seconds, would be displayed on the screen. This served as a delay to allow the participant to record down their interpretation. It was also designed such that the participants would record down their first impression of the gesture. First impression remained an important factor that influenced buyers into purchasing things such as toys. When the user had finished watching the 25 human gesture videos, it marked the end of the first part of the experiment. At this point, the questionnaire would be collected and the participant would be instructed to leave the room for a short break of 30 minutes. This break allowed the participant to shift his attention away from trying to memorize the human gesture previously shown.



(a) Frames taken from a *human* gesture video



(b) Frames taken from a *robot* gesture video

Fig. 2. Frames taken from the videos during the experiment

After the break, the participant proceeded into the second part of the experiment. This involved running pre-recorded videos of 25 robot gestures to the participants. In the preparation of this video, our social robot with 10 DOFs would be used to execute the gestures individually. This was to standardize viewing of the robot gestures for all

the participants and eliminate the possibility of encountering mechanical errors in the execution of robot gesture during the experiment. The same example of a hugging robot gesture video in still frames could be seen in Fig 2b.

Prior to the execution of this second phase, the participant would again be provided with a different sheet of questionnaire to record his interpretations of the robot gestures. Similarly, videos of the robot gestures would be screened to the participant one at a time, accompanied by the same black transition screen of five seconds to allow the participant to record the gesture on the provided questionnaire. Upon the completion of viewing all the 25 robot gestures, the participant would be given an additional five minutes to rate on two attributes of this experimental study. The two attributes questioned the lifelikeness of the robot gesture as well as how much he liked the gesture.

3 Results and Discussions

Fig. 3 showed the results of the human perceptions on human gestures while Fig. 4 showed the results of the human perceptions on the gestures by the robot. In terms of accuracy, at least 75% of the subjects understood 64% of the human gestures as shown in Fig 3 and 56% of the robot gestures as shown in Fig 4. The gestures on “nodding”, “signaling left”, “hugging” and “don’t know” shows excellent relationship between human gesture and robot gesture. Fig. 4 shows that these gestures are recognized perfectly by our participants. Moreover, it also shows that the participants have no difficulties in identifying the link to the human gesture, showing that the human-likeness character is not critically affected. However, there were four gestures with poor results, which were “praying”, “driving”, “drumming” and “push pull” exercise, and they were due to varying interpretations in different contexts. From these, it could be verified that a reduction in number of joints to 10 DOF for these gestures had been successful and to achieve a human-like behavior in a robot gesture, a similar upper body structure could be implemented. Visually, Fig 5 showed that there were no severe difference in the subjects’ response for both human and robot gestures. In particular, six gestures provided the matching perceptions for both gestures, confirming the success of the robot mimicking the human gesture.

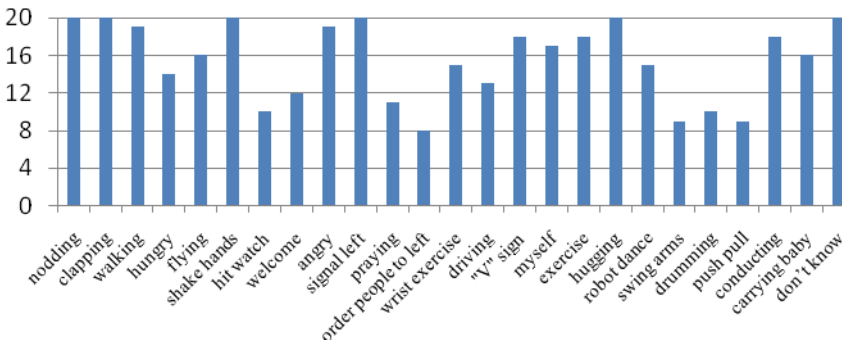


Fig. 3. Plot of subjects’ perceptions of human gestures

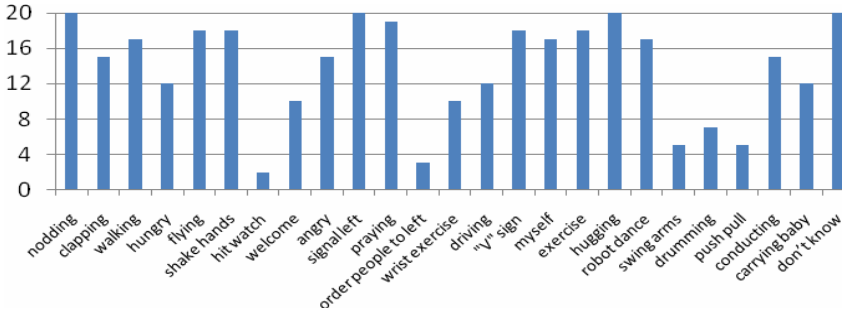


Fig. 4. Plot of subjects' perceptions of robot gestures

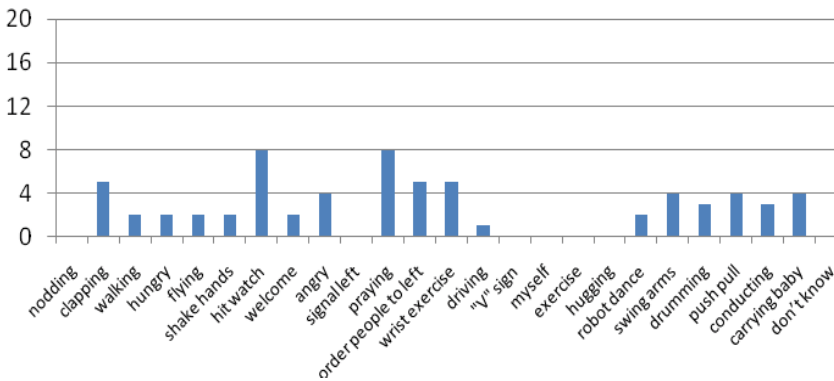


Fig. 5. Plot of difference in subjects' responses between human and robot gesture

Additionally, a Chi-Square Test of Homogeneity was conducted on these results to examine the success of the robot in mimicking the human gesture. With the null hypothesis that the probability in each cell is equal, a Chi Square statistic of 14.05 and 24 degrees of freedom with a p value of 0.95 is calculated. For a significance level of 0.05, it is seen that since the p value is larger than 0.05, the null hypothesis is not rejected. This means there is hardly any significant deviation in the human-likeness of the robot gesture, showing that the robot has been successful in imitating the various human gestures. Results have shown that a robot with 10 DOF on the upper body is acceptable in mimicking a real human gesture.

With regards to the participants' ratings on the robot gestures shown during the experiment, as shown in figure 6, all the participants rated an average of 4.85 out of 5 when asked how much they like the gesture and would like to see its implementation on a robot. Also, they rated an average of 3.35 out of 5 for the human-likeness of the robot. These positive results suggest that the general public is acceptable with the gestures shown through this robot of reduced DOFs. Hence, we see that this would pose as a huge opportunity for the toy industry. A favorable score for the public's fondness for such gestures is a plus point for toy manufacturers, as it forms the fundamental basis for customers to purchase their products.



Fig. 6. Participants' ratings on robot gesture

4 Conclusion

We have verified that the human-likeness of human gestures is not greatly affected by a reduction in the number of DOF from the conventional upper body of 14 DOF to the reduced number of 10 DOF. From the results, we see that for a 10 DOF robot, it is capable of carrying out 15 gestures, namely nodding, clapping, walking, flying, hand shake, angry, signal left, praying, 'V' sign, myself, exercise, hugging, robot dance, conducting and don't know. Our findings indicate that this approach is feasible and useful, and this can lead to a reduction in build size as well as being cost effective. Its implications to toy robots include reducing the cost, size and weight of the toy, while still capable of communicating human-like gestures with their buyers. Furthermore, the gestures have also been shown to be readily accepted by the public.

In this paper, implementation was only done on a 10 DOF robot. As with the success of the results, we propose that future works can be done to further investigate the ability of the robot to execute human like gestures given an even reduced number of DOFs such as 6 DOFs or 8 DOFs. In addition, more gestures can be investigated to further justify the effectiveness of a 10 DOF robot. With the additional results, an optimum number of DOFs needed to obtain the maximum number of recognizable gestures can be determined.

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STB: Intentional Stance Grounded Child-Dependent Robot

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Abstract. This paper reports on a children-dependent robotic approach to establish asynchronous child assistance with a social rapport network for the purpose of collecting trash from a public space. Our sociable trash box robot (STB) was unable to collect trash by itself. However, it did succeed in conveying its intentions to collect the trash from children. The main purpose of this study is to investigate the effective social cues, behaviors, and other essential factors to facilitate children in their anticipation of the behavior of a sociable trash box robot. The STB engages by using interactive social cues and vocal interactions to build a social coupling with children in order to induce their assistance in collecting trash. We discuss the minimalism designing mechanism of the STB, as well as the effectiveness of the above factors through an experiment which is conducted in a child-centric environment.

Keywords: Children-dependent robot, sociable trash box, designing mechanism, and social cues.

1 Introduction

There is a need to encourage society to interact with robots in a more entertaining, engaging, and seamless manner as a collaborator or assistant, rather than merely use robots as tools for daily assistance [9][15][1][4]. These types of robots would afford a significant role in society, which can be conveyed to any person for the purpose of utilizing them as well as collaborating with them [3]. Recent HRI research has indeed attempted to address the above problems through the field of sociable robotics [12][16][10]. A sociable robot can be defined as participating in social interactions with people in order to satisfy some internal goal or motivation [2]. Based on the above attributes, researchers have attempted to invent a sociable robot which can be supportive to humans in their daily lives and provide them with assistance for distinctive requirements [7][17]. Social cues have thus become essential factors in understanding a partner's internal states, which can be significant for humans and robots to align and synchronize their anticipations [5].

As a new direction in the study of sociable robots, researchers have been designing artifacts as a sociable robot, e.g., an AUR lamp robot [6] and a RoCo sociable display [14]. We believe that humans would rather engage and enjoy themselves with the above sociable creatures while using them in their daily lives. AUR is capable of directing its head and different locations based on human social cues such as hand gestures and vocal interactions. This kind of robot provides a rich social interface to communicate with humans while collaborating with the human task efficiently. The robot is capable of understanding human intentions, which is the most important factor in creating the trust and social rapport necessary to accomplish a task.

There has been significant controversy regarding the use of robots to do the work of humans, resulting in a societal need to establish a respect or a trust relationship with robots [11]. For this purpose, we believe that the concepts of a human-robot collaboration and human-dependable robot are desirable and should be used efficaciously. Tweenbot [8] is a human-dependent robot that navigates with the help of a human pedestrian. However, a tweenbot displays a terminus on a flag whereby a human reads the flag to determine (or target) the correct direction to reach their goal. The results showed that people assessed the robot's intention through the flag (reading the destination), which can help the robot reach its goal. The simple social interactions create a complex network by human intelligence and asynchronous interactions. Based on these findings, we believe that instead of expressing a robot's intention through a written message, it would be more ideal for the robot to use rich social behaviors (a social interface) in order to convey its intention to humans.

At the core of a human-dependent robot is a need to acquire assistance (or collaboration) from humans to terminate a task. To gain this assistance, the robot must convey its intention, or the human must predict the intentional stance through the robot's behaviors. Due to the above controversy, it is apparent that the robot needs to use desirable behaviors to manifest its intention or goals. Therefore, the use of social cues for interactions and human-like communication capabilities are essential factors for achieving the concept of a human-dependent robot. Still, we have to investigate the desirable cues or behaviors of robots based on the contexts. It is also important to examine a robot's shifting behaviors to convey its goals based on the environmental conditions and human behaviors. As a novel concept, we have developed an STB as a child-dependent robot that can collect the trash by conveying its intention to children within a public space. Moreover, it is important to attempt to establish asynchronous child assistance with a social rapport to collect the trash from a public space. In this paper, we examine the benefits of an STB mechanism and investigate how STB behaviors are effective in transferring intentional stances to evoke children's social interactions and assistance in collecting trash in the environment.

2 Child-Dependent Sociable Trash Box Robot

Our main objective is to obtain child-assistance in collecting trash from a public space, while establishing a social interaction between the child and the robot



Fig. 1. Children interacting with the sociable trash box robots

(Figure 1). Our robot is capable of displaying manifold affiliation behaviors to build social rapport with the goal of collecting trash in and around an environment. In particular, the STB is a child-dependent robot that walks alone in a public space for the purpose of tracing humans and trash and collecting trash. In a crowded space, STBs move toward trash by engagement, using an attractive twisting motion (behaviors) and vocal interaction to convey its intentions to children. The robot is incapable of collecting trash by itself. In this sense, children have to infer the intentional stance of the robot or expectation for interaction with the STB. It is a novel concept to be able to collect trash while creating social rapport with children. The robot engages by using twisting and bowing motions as children place trash into an STB container. In order to collect the trash, each of the STBs communicates with one another to create a distance between one another to avoid collapsing.

3 STB Designing Concept

Figure 2 depicts our proposed STB designing concept, which is implemented with the minimalism designing mechanism. The STB has two parts on its body (upper

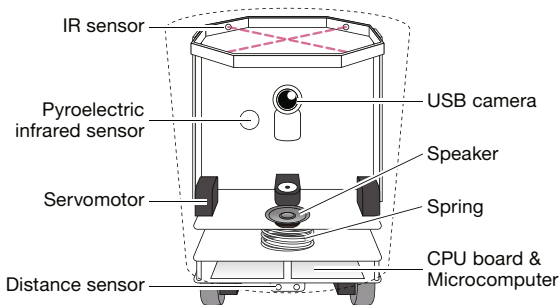


Fig. 2. The above robot, designed with the minimalism designing concept, assists in motivating children to establish social rapport with the STB

and lower), and the upper part contains three servomotors: one for twisting itself to the left and right, and the other two motors for bending forward and backward. The lower part has two servomotors for moving its entire body to the left and right directions. It contains three kinds of sensors and a single camera to obtain environmental informatics: a pyroelectric infrared sensor, an infrared ray sensor (IR sensor), and a distance sensor. The pyroelectric infrared sensor is capable of tracing human body temperatures which are then used to discover the crowded space, while the IR sensor traces whether trash has arrived to its container. The STB utilizes a distance sensor for avoiding obstacles and to create distance between other STBs. A single webcam is used for both trash detection and recognition of other STBs through image processing. The robot preserves the following procedures to discover trash in the environment: the STB initially uses distance sensors to discover objects in the space. If an object is discovered, optical flow is then utilized to recognize whether it is a moving object or not; if it is a moving object, the robot decides if it is another STB or a human; otherwise, the robot determines that the object is trash. To move the object, image processing is employed to recognize other STBs (through color detection); otherwise, the temperature is estimated using a pyroelectric infrared sensor to discover the presence of a human in the space (Figure 3).

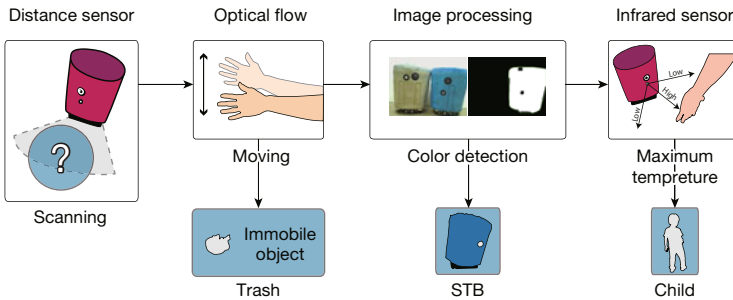


Fig. 3. The overall STB process which assists in discovering the trash and the human in the space

4 Experimental Setup in Child-Centric Environment

The concept of a human-dependent robot is unique in the field of social robotics. Accordingly, we have to investigate how to implement and design the above concepts into human-centric environments. The biggest challenge is being able to evaluate a child's mental properties about the robot's intentional stance. However, if we combine the relevant contexts (environmental condition) with the robot's behaviors and also carefully analyze their (child or human) behaviors (reaction or feedback), we can quantify or predict their mental properties [13].

To evaluate the effectiveness of the child-dependent robot (STB), we conducted an experiment using a natural setup of a child-centric environment as a public space. It was important for the experiment to be conducted in a natural

Table 1. The table shows the child’s behaviors are based on the STB’s action scenarios: PT (children place trash into the STB’s container), and DPT (children have not placed trash into the container)

STB’s Action Scenarios	Child’s Behaviors		
	Int-to-STB	Ind-Int-STB	St-Colt-Trash
MT-I	PT=0, DPT= 9	PT=10, DPT= 0	PT=3, DPT=3
MT-G	PT=0, DPT= 6	PT=8, DPT= 5	PT=4, DPT=7
MC-WC	PT=0, DPT= 5	PT=3, DPT= 2	PT=6, DPT=8
MC-C	PT=0, DPT= 4	PT=2, DPT=13	PT=4, DPT=6
NMB	PT=0, DPT= 0	PT=1, DPT=3	PT=2, DPT=5

setting in order to obtain the precise outcomes to effectively implement the above robots into society. We conducted the experiment in a Developmental Center for Children, and evaluated the validity and effectiveness of the approach through five action scenarios: move toward trash (MT-I), communicate (electronically) with other STBs to move and create a distance with them (MT-G), move to a crowded space without communicating with other STBs (MC-WC), move to a crowded space to communicate with other STBs (MC-C), and STBs do not move and behave (NMB). When looking attentively at the videos, we categorized three main behaviors of the children: interest to the STB (Int-to-STB), indirect interaction (showing the interests far from the STB) with the STB (Ind-Int-STB), and state of collect the trash to the STB (St-Colt-Trash). The following Table 1 shows the behaviors of the children based on the STB action scenarios.

We attempt to link the trash box action scenarios with the children’s behaviors (reactions or feedback) in the contexts of trash collection from the child assistance. The above link helps to envision the (children) inferring behaviors of the STB (intentional stance) in terms of mental properties. Our approach assumes that the children’s mental properties can be elicited through their reactions (feedback or behaviors) based on the robot’s behaviors. In the present experiment, 108 children (between the ages of 4 and 11 years old) participated in naturally interacting with the STBs.

4.1 Moving vs. Immobile STBs

A chi-square test was employed to determine if either the STBs’ movement or immobility (fixed as a typical trash box in the corner) was independent of the collection of trash. Each context was tested separately. The resulting p-value ($\chi^2=6.87$, d.f.=1, $p=0.009$) was less than the critical p-value of 0.05 for the STB movement scenario, while in the case of the STB immobile scenario, the p-value ($\chi^2=1.31$, df =1, $p=0.252$) was greater than the critical p-value of 0.05. The results therefore indicate that the null hypothesis can be rejected in the STB moving scenario and that a significant relationship exists between the two groups. However, in the STB immobile scenario, the null hypothesis cannot be rejected, indicating nonsignificant relationship between the two groups. The results of the

above statistical method therefore reveal that the STB movement was essential in conveying its intentions toward collecting trash.

4.2 STBs Moving Direction Toward to Trash vs. Toward to People

In the former experiment, we discovered that the STBs' movements were most important in collecting the trash with child assistance. Accordingly, we have to reveal the direction of the STB, whether it is toward trash or toward people, in order to evoke its intentional stance in the children's minds. We therefore employed a chi-square method to evaluate the relationship between the trash (STB movement) and the trash collection from the children. The resulting p-value ($\chi^2=9.35$, d.f.=1, $p=0.002$) was smaller than the critical p-value of 0.05. These results indicate that the null hypothesis can be rejected and that the two groups have a significant relationship. We applied a similar procedure for the context of STBs moving toward people, with a resulting p-value ($\chi^2=2.38$, d.f.=1, $p=0.123$), which was greater than the critical p-value of 0.05, meaning the null hypothesis can be rejected. This reveals that the STBs' movement toward the children did not correlate with the collection of the trash with child assistance.

4.3 STBs Moving (Interacting) as a Swarm vs. Individually

In this phase, we were interested in discovering whether the swarm behaviors (moving around public space as a group) or individual behaviors (moving around public space individually) were more effective in triggering the intentional stance of the STB in the children's minds (Figure 4). We considered the behaviors of the child subjects (Int-to-STB, Ind-Int-STB, and St-Colt-Trash) with the STB action scenarios of MT-I (individual behaviors) and MT-G (swarm behaviors). For this purpose, we employed a chi-square test to verify the relationship of the robot's demeanor (behavior as individual or group) and the trash collection via the child assistance. The results revealed that the p-value ($\chi^2=4.00$, d.f.=1, $p=0.046$) was less than the critical p-value of 0.05, indicating the null hypothesis can be rejected and that the STBs' demeanor (individual or group) had a strong relationship with the trash collection. When carefully analyzing the contexts, we



Fig. 4. STBs moving around the public space individually and in swarm interactions

found that when the STBs moved in a group, many children (70%) interacted with the STBs compared with when the STBs moved individually (i.e., only 30% children participated to the interaction). In this sense, we believe that the group movement of the STBs more effectively helped to convey their intentions and to establish social rapport with the children than when the STBs moved around individually in the space.

5 Discussion

Movement is a main characteristic used in gaining the attention of people or animals. We believe from the above results that characteristic of attention-grabbing is gaining more consideration as an effective means in inferring an object (e.g. robot) or people's behaviors. Another important aspect is the use of rich social cues (e.g., vocal interaction or twisting behaviors) based on the contexts, as these factors help to map various perceptions to infer someone's behaviors, e.g., intentional stance about an STB. We can examine similar perspectives by way of inferring a robot's behavior in a child's mind. Accordingly, the results suggest that the STB movements directly correlate with the trash collection from the child assistance.

A second important factor in collecting trash is that robot has to move toward the trash in the space. In this context, we believe that several attention procedures are used to coordinate and synchronize the child's perceptions. However, when the STB moves toward the trash, the child might be able to predict its direction or path. When a child's attentions coordinate with the trash in the direction of the STB, the child is then motivated to map the above perception to predict the STB's intentions (Figure 5(right)). Accordingly, the child is processing several attention processes with its own perception to infer the intentional stance of the STB.

The results showed that the context of STBs moving as swarm had a strong effect in gathering children in the public space and in establishing social rapport with them to collect the trash with their assistance. The above grouping behavior was effective in gaining the attention of the children. During the movement, the STBs communicated with each other and moved toward the trash, which made the children curious about the STBs' behaviors and intentions. In this sense, we believe that the children considered the STB as a creature. There are different types of trash (e.g., pet bottles, cans, etc.) in a public space. By examining the STB swarm (three STBs) we see that the children were motivated to place the trash into the STB's containers that separated the different types of trash.

5.1 Most Effective Factors for Conveying STB Intentions

We were interested in extracting the most effective factor to convey the STB's intention through correspondence analysis. Correspondence analysis is a descriptive technique designed to analyze simple two-way and multi-way tables through graphical representation, and it is helpful to measure the correspondence between the groups (row and column). In our approach, we were interested in determining the relationship between the state of trash collection and effective factors to

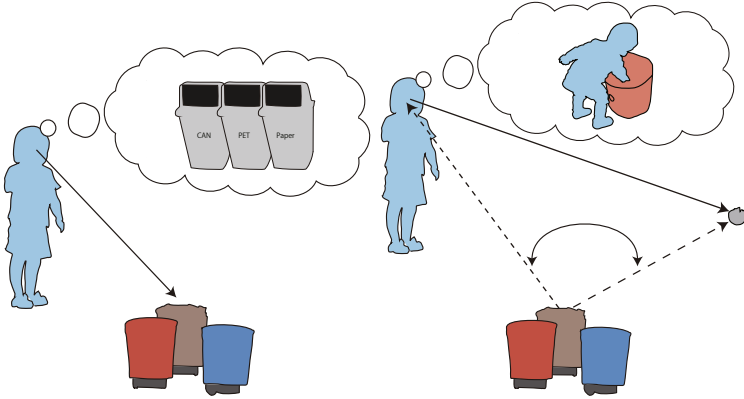


Fig. 5. In the left figure, the child attempts to infer the STB’s intention by combining its movement, social cues, and shape, which are equalized into a typical trash box. In the right figure, the child attempts to predict the intentional stance of the STB by mapping it with the environmental condition (availability of trash in STB’s path).

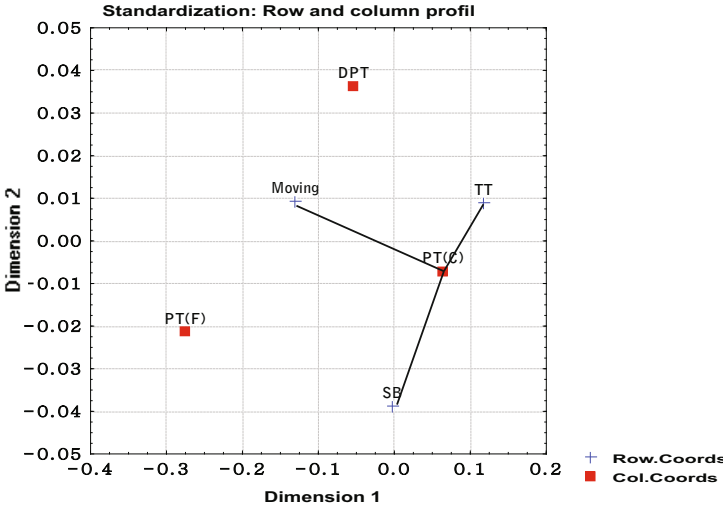


Fig. 6. Relationship between the different states of trash collection (child comes close and puts out trash, a distant child putting trash into the STB, and uncollected trash) and various effective factors (STB moving, STB moving toward trash, and STB behaving as a group). The resulting states include: PT (C)-child coming closer and putting out trash, PT(F)-from far away a child throws trash into the STB, DPT- uncollected trash, Moving- STB moving with attractive social cues, TT- moving toward the trash, and SB- Swarm behaviors.

evoke the intentional stance about the STBs in the children's minds through a graphical representation. The above representation was helpful in eliciting the most effective factor to convey STB intentions to collect the trash from a public space. A variant of the Euclidean distance was used to measure and depict the distance between profile points. Figure 6 represents the results of the correspondence analysis which shows the relationship between each profile points. The above figure reveals that the trash collection and STB behavior toward the trash had the smallest distance. It clear that STBs had to move toward the trash, and that this was the single most effective factor for the robot in conveying its intentions to the children.

When the children watched the STBs move in the environment, they simultaneously received much information (e.g., the shape and movement of the robot path, etc.) regarding the STBs and the environmental conditions. These perceptions were effective in predicting the intention of the STBs in the child's mind. Also, other stimulation of attention helped to coordinate or match their perception to interpret the information to obtain meaning for it (intentional stance of the STBs). The above results thus revealed that our child-dependable robot was capable of establishing social rapport with the children, and it also helped to develop its social interaction skills while collecting the trash from public space.

6 Conclusion

In this paper, we have proposed a child-dependent robot called an STB to collect the trash from a public space. Indeed, this is the concept of a child-dependent robot (collecting trash from assistance of social interactions with children) by functioning precisely in a child-centered environment. The novelty of the approach was to evoke an intentional stance about the STBs in the children's mind. The experimental results showed that moving, moving toward trash, and behaving as swarm were the most effective factors in fulfilling the above purposes. Also, a correspondence analysis showed the STB movement toward the trash to be most effective factor in triggering an intentional stance about the STBs.

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Using the Interaction Rhythm as a Natural Reinforcement Signal for Social Robots: A Matter of Belief

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Abstract. In this paper, we present the results of a pilot study of a human robot interaction experiment where the rhythm of the interaction is used as a reinforcement signal to learn sensorimotor associations. The algorithm uses breaks and variations in the rhythm at which the human is producing actions. The concept is based on the hypothesis that a constant rhythm is an intrinsic property of a positive interaction whereas a break reflects a negative event. Subjects from various backgrounds interacted with a NAO robot where they had to teach the robot to mirror their actions by learning the correct sensorimotor associations. The results show that in order for the rhythm to be a useful reinforcement signal, the subjects have to be convinced that the robot is an agent with which they can act naturally, using their voice and facial expressions as cues to help it understand the correct behaviour to learn. When the subjects do behave naturally, the rhythm and its variations truly reflects how well the interaction is going and helps the robot learn efficiently. These results mean that non-expert users can interact naturally and fruitfully with an autonomous robot if the interaction is believed to be natural, without any technical knowledge of the cognitive capacities of the robot.

1 Introduction

The question of how to have robot able to be useful and adaptive in our socially situated environment is of growing interest. Indeed, in a not so far future, human will have to interact daily with robots in various settings. During these interactions, robots will have to gain information from humans, and humans will have to learn from robots. Concerning the non-verbal aspects of these interactions, the field of developmental robotics has been trying to develop and study algorithms and architectures as generalisable as possible, in order for these systems to be as

minimal as possible, be that on the lower motor level [1] or at the motivational level [2]. The underlying principle of the field is to try and model phases and phenomena from the development of children and animals to understand and take advantage from the adaptivity and efficiency we observe in them.

Within this framework, the authors have been interested in defining and testing how and when learning from a human partner can be achieved with the minimum amount of prior knowledge from the robot, as a young infant has to do in the early years. During this period, the most important partner the infant has is its mother, or primary caregiver. As described by Bowlby in [3], the infant uses the attachment figure, often the mother, as a secure base to explore and learn from its experiences in unknown situations. However, the question is how does the mother elicit these positive responses and promotes healthier cognitive and socio-emotional development. One hypothesis is that the mother’s sensitivity, as described in [4], or consistency in the mother’s behaviour and responses to stimuli is crucial. The positive emotions and mutual delight that mother promotes a healthier development for the infant, and deep engagement from the mother [5]. Additionally, within the still-face paradigm [6], where a caretaker would produce a neutral expression after a few minutes of interaction which in turn would produce a significant fall in the infant’s positive responses. Other frameworks like the Double Video paradigm, for instance [7], measured the same responses when the synchrony of the interaction was altered by introducing time delays in the mother’s response. This would indicate that synchrony and timing during a mother-infant non-verbal interaction is a strong indicator of the infant pleasure and emotional responses.

Defining the notion of sensitivity in the context of human-robot interactions is far from trivial. The experiment discussed in this paper is based on our previous work [8][9][10], where was raised the question of how important the consistency of the behaviour of the human to the stability and accuracy of learned sensorimotor associations. We attempt to unify these notions in order to build a general reinforcement signal that could be used by a robot in a large number of settings, which in turn would help humans interact with robots without any knowledge of how the robot cognitive system is designed.

We here present an experiment where a NAO robot has to learn, without any prior knowledge, the correct sensorimotor associations in a “mirroring game”. The actions of the human are mediated by a pink ball, and the robot uses the rhythm at which the human is performing a new action in order to reinforce the correct action to perform. This experiment is an extension of the work presented in [11], where the same algorithm was used in a human-computer interaction, and [12] where the setup was extended to work on an AIBO robot and then a NAO robot.

The results showed that the rhythm could be used as a reinforcement signal for the robot to learn the correct associations, even more so when the principle was explained, since they would explore all possibilities they know of. But the non-expert subjects, who are not used to interact with robots and do not know the rule, did not significantly manage to teach the robot the associations.

If the rhythm of the interaction is, as hypothesized, an intrinsic component of a natural, surely something was missing for the non-expert user. The modified version of this experiment presented here aims at discovering what was missing in the interaction for these subjects to succeed.

2 Architecture and Experimental Setup

In our setup, the robot is trying to learn to mirror the actions of the human partner, following the position of a pink ball in its visual field, as in Fig 1. The robot has to learn the four different sensorimotor associations, corresponding to the four possible positions (left arm up when the ball is in the top right of the visual field, left arm down when the ball is in the bottom right, and respectively for the left side). The learning algorithm itself functions as follows and the main components are depicted in Fig 2.

The robot has access to four different perceptions (ball in the top-left part of the visual field, ball top-right, ball bottom-left and ball bottom-right) to which it will associate an action. Every time an action is performed, the rhythm prediction component will reset and peak after a time corresponding to the last gap learned between two actions. To summarise, the robot learns in one-shot the time elapsed between two different perceptions, and expects the next action to be performed after this precise duration. The reinforcement signal is calculated as the difference between the duration expected and the duration observed. The



Fig. 1. Experimental setup. The human partner is in front of the robot, moving a pink ball between the four different positions in the visual field. The robot learns the proper response to mirror the actions of the human partner.

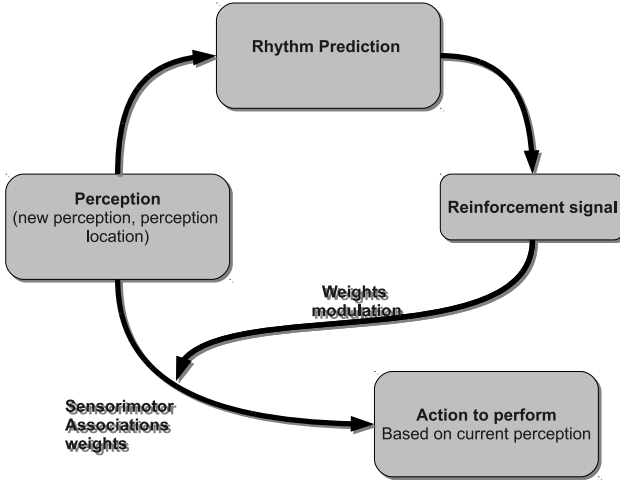


Fig. 2. Abstract representation of the robot architecture to learn the sensorimotor associations

only prediction made here is the occurrence of the next action from the partner, which for the robot is an change in the current perception.

The reinforcement signal $\mathbf{R}(t)$ from the rhythm prediction module varies as a Gaussian centred on the time t , which is the time of the next predicted event (see [11] for more details). $\mathbf{R}(t)$ is then used to change the weights between two fully connected layers of neurons (the perception and the action to be performed). The synapses have a weight W_{ij} and a probability p_{ij} associated to them, and the rule used is the **Probabilistic Learning rule**. Using this rule, a fully connected neural network (perceptions connected to potential actions) behaves as follows:

$$\Delta p_{ij} = (\epsilon + \alpha \times R(t)) \times C_{ij} \quad (1)$$

$$p_{ij}(t) = H(p_{ij} + \Delta p_{ij}) \quad (2)$$

With ϵ the learning speed, α the reinforcement factor and C_{ij} the average of the past activation of unit i . Then, if a random draw $Rand$ is higher than the confidence, $Rand > p_{ij}$:

$$W_{ij} = 1 - W_{ij} \quad (3)$$

$$p_{ij} = 1 - p_{ij} \quad (4)$$

Using $Rand$ promotes an exploratory behaviour when the confidence is low, and a more exploitative behaviour when it is high.

3 Experimental Design

The aim of the experiment is to assess if and how the human subjects are able to teach 4 different sensorimotor associations without any explicit feedback or

reinforcement signal being used by the robot, and without the human having a prior knowledge of the signal used by the robot. If the humans are successful in that task, this will show that the rhythm is potentially an intrinsic component of non-verbal interaction that can help identify successful interaction and allow a robot to learn **without any specific reward**.

In order to keep the subjects engaged and to make the robot's behaviour appear slightly more life like, we introduced a slow balancing movement on the robot. Its torso would lean closer to the human partner and then slowly back away with a low frequency modulated by the rewards obtained over time. Moreover, in the architecture, a notion of **well-being** has been added in order to control the expressions of the robot. We therefore decouple the reward used to learn the sensorimotor associations and the overall behaviour of the robot. The robot will express happiness when the **well-being** is high, and sadness when it is low, and boredom when it is low and the perceptions stay too stable when the human is always repeating the same action over and over.

Finally, one major change was in the protocol of the experiment. Regardless of the background of the subject, they would all hear the same guidelines which are as follows: *You will be asked to use the pink ball to teach the robot to mirror your actions. The robot is able to hear your voice, but does not understand words. The robot is able to see your face and what you are expressing. The robot will only respond to movements (a change of the position of the ball in its visual field). The LEDs in the eyes of the robots will reflect the quadrant where the robot perceives the ball, and are turned off when it cannot see the ball any more. Try and act as though you were teaching this to a 6 to 15 month old infant, who is able to process voices and faces.* As a monitoring feature, we also reflected the expected rhythm in the LEDs of the robot, as an indicator for the experimenter to see how the system was performing. The LEDs would turn to a brighter white the closer to the predicted action we got, and then fade the longer after the predicted action. The guidelines were modified to provide the human with potential existing and natural rewards (tone of voice and facial expressions) they can use without having to be trained. This was also believed to raise their confidence in the overall capabilities of the robot.

We conducted a study with 10 subjects, with ages ranging from 23 to 60 years old, and with various backgrounds. The robot used was the same which was used previously, the NAO robot (Fig. 1). The interaction would last typically ten minutes, and was ended by the experimenter. We recorded the value of the rhythm used by the human, the movements performed by the robot, and the rewards the system identified. Using this we have enough data to know what rhythm a particular subject used in a particular situation (for instance which one was used when the robot was right, when it was wrong, when it was wrong for a long period of time, etc.). We also asked the subjects to fill in a questionnaire, designed to rate how the body postures of the robot helped the users and how they were identified. The questionnaire also asked the subject what kind of cues they thought the robot was using to learn, choosing from 4 choices: facial expressions, tone of the voice, rhythm of the humans action, the repetitiveness

of the action(explained as repeting the same action over and over consecutively), or free choice. The subject could select any number of these, if they thought the robot actively used them.

4 Results and Discussion

4.1 General Observations

Firstly, the subjects seemed far more engaged and showed less frustration during the experiment then when the expressivity was not displayed and when they did not know that the robot could use the voice and the face as available social signals. Only two of them seemed to want to stop the interaction after more than 7 minutes. All the other sujetcs were disappointed to stop the experiment after ten minutes, since they managed to teach the robot to mirror their actions successfully several times. Since this setup still allows the system to interpret false negatives, the robot was forgetting the correct actions and then the subjects were keen on trying to make the robot learn again. Every subject successfully managed to teach the robot at least 3 correct associations, which is far more than in the previous trials, even when the sujetcs were told that the rhythm was used by the robot to learn. After a first phase of success, where the robot had learned successfully, the subject would accidentally cross another area of the visual field, changing the rhythm, leading the robot to forget an association, which would disturb the human, leading to further mistakes. This is one of the major problems of this setup. The system is prone to pick up false negative really easily.

4.2 Objective and Subjective Reinforcement Signal

During a successful period of the interaction, the subjects would typically encourage with a “Yes” or “Very good”, or any other short positive phrases when the robot was performing the correct action, using an exaggerated tone, as parents or adults use with young infants. Alternatively, they would also use “No” or “Not that” in the case of a wrong action being performed. But they did use a different rhythm consequently to a good or a wrong action of the robot, which leads to a meaningful reinforcement of the associations.

As can be seen on figure 3, when asked what signal they thought the robot used, 90% of the subjects picked the tone of voice as the main cue to learn the correct associations. Although most of them during the experiment were expressing the fact that at first their voice did not have any impact on the behaviour of the robot, when they managed to teach one or more associations to the robot, they would go on using their voice as a signal for the robot to use. Moreover, it suggest that the whole behaviour of the robot, was believable and consistent with what the subject would expect from an agent using natural cues in order to be taught a simple task, producing in turn a smoother and relaxed behaviour from the subjects, using implicitly the rhythm. Also, when the subjects were asked what they thought the white LEDs were reflecting, none

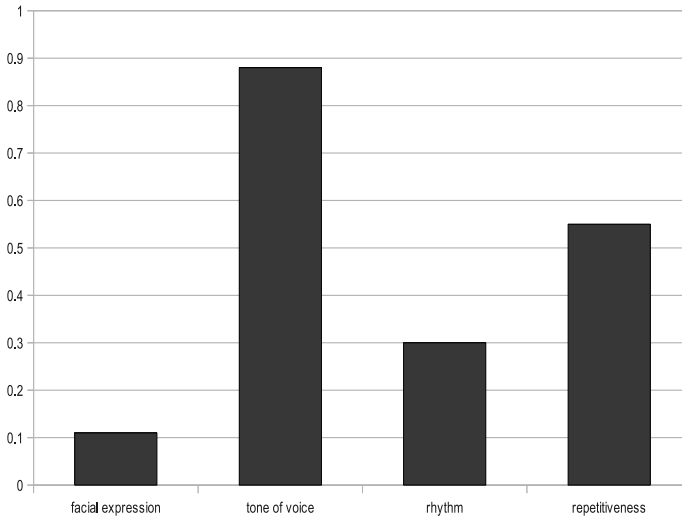


Fig. 3. Subjects rating on what signal is used by the robot to learn the correct associations. Although the tone of voice was not used by the robot, almost 90 percent of the subjects described it as a cue used by the robot to learn.

of them identified them as an expectation of an event, or anything related to the rhythm. This suggests that this cue was not biasing their behaviour and that their focus was mainly on the task at hand. Finally, when asked about the relevance and coherence of NAO's body postures, the subjects expressed that some of them were slightly confusing (the happy and bored postures), but the sad posture, displayed when too many negative rewards were experienced, was rated as good, but more compared to frustration or disappointment.

5 Conclusions and Perspectives

The results of this experiment are promising as they indicate that the rhythm of the interaction can be used as a reinforcer to learn new sensorimotor associations without prior knowledge to the robot or the human. This system seems to be even more efficient when the human partner is unaware of the underlying mechanism and behaves more naturally, using the usual cues people would use with a young infant such as the voice and the facial expression. We argue that this was made possible by making the robot more life-like, never really as still and predictable as a usual machine would be, but mainly by pushing the subjects to believe that the robot could process information as a young infant would, namely the tone prosody of the voice and facial expressions of the partner. Therefore, if research goes on towards making robots use synchrony and rhythm, as young infants use during non-verbal interactions, the success will depend on the belief and confidence of the human in the capabilities of the robot.

Once the human partner believes he can act naturally without any guidelines and coaching from expert users.

These results are also consistent with the ones found in [10], where subjects rated the behaviour of an Aibo robot having two sets of parameters rendering it more or less needy and reactive towards events and interactions with humans. The more reactive, moving and consistent the behaviour, the easier it was for the human to interact with the robot. From a long term perspective, if the results found here are confirmed by a more extensive and broader study, the rhythm or other synchrony related measures could be used by a robot to evaluate the potential of a human partner in becoming a reliable teacher or learning partner. Indeed, in the future if robots meet an increasing number of humans, and will need themselves assistance, knowing which partner is the most useful should be a clear advantage. In comparison with humans, who from birth do not choose their human partner in term of socio-cognitive development, the robot could actually choose carefully its primary caregiver(s).

In the future, we plan on confirming these results with a broader set of subjects, in age, technological and cultural background. We would then be interested to see with what kind of different interactions the rhythm can be used. Finally, we would work at extending the architecture to allow different “natural” reinforcement signals to be used by the robot. We would then be able to study the possibility of conflicts between these signal and develop a system which would try and cope with the possible contradictions.

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Case Study of a Multi-robot Healthcare System: Effects of Docking and Metaphor on Persuasion

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Abstract. This paper reports the docking and metaphor effects on persuasion among multi-robot healthcare systems. The goal of our research is to make a robot friend that lives with its users and persuades them to make appropriate healthcare decisions. To realize such a robot friend, we propose a physical approach called docking as well as a contextual approach called metaphor to perform relational inheritance among multi-robot systems. We implemented a multi-robot persuasion system based on the two approaches and verified its effectiveness. The experimental results revealed that users emphasize interpersonal relationships to decide whether to follow the robot's advice when utilizing the metaphor approach, and that users emphasize robot aggressiveness when utilizing docking approach.

Keywords: Persuasion, Multi-robot healthcare system.

1 Introduction

The goal of our research is to develop a multi-robot healthcare system to persuade users to take actions to prevent healthcare problems in the early stage of their lives so that they can remain healthy. Our multi-robot healthcare system consists of two kinds of robots, virtual and visible. Both have different aspects. The virtual-type robot is an embodied conversational agent working on mobile devices. Users can easily take it anywhere and keep in touch with it. The visible-type robot has an actual body and interacts with users by gestures and utterances. It will be placed in offices or hospitals so that users can easily access its healthcare information whenever they want. By collaborating with these two different types of robots, we believe that the system can provide daily healthcare support to users. Our research aims to determine an effective way to persuade users by collaborating these two types of robots.

Many factors affect the persuasion of system users. In this research, we focus on establishing the credibility of the robots (See Section III for more details). B. J. Fogg argued in "Persuasive Technology" [1] that credibility consists of two different dimensional spaces: authoritativeness and believability. He defined authoritativeness as knowledge, skills, and the experiences of the information source. On the other hand, he defined believability as the fineness and the morality of the source. The most credible information source has both authoritativeness and believability at a higher

level. For humans, one of the most credible sources is a close friend who is an expert in a particular area of interest. Our target is to establish this relationship between users and robots in multi-robot healthcare systems. Considering the merits and demerits of virtual- and visible-type robots, the former are portable with easy access, so creating a close friend relationship with users is effective. The visible-type robot is located in such places related to healthcare as hospitals and has rich body expressions so that it can effectively suggest expertness; however establishing a friendly relationship is difficult. Thus our strategy must find out how to inherit the relationship established by the virtual-type robot toward the visible-type robot shown in Fig. 1.

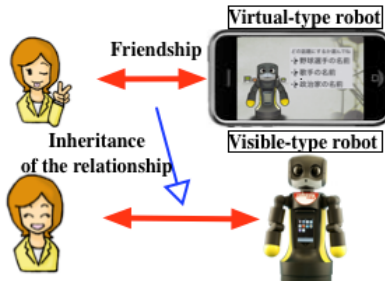


Fig. 1. Concept of our strategy

In this research, we proposed a physical approach called *docking* as well as a contextual approach called *metaphor* to inherit the relationship from a virtual-type robot to a visible-type robot. Docking, a physical user action that connects a mobile device to the visible-type robot, results in appropriate animation on the virtual-type robot and an appropriate reaction from the visible-type robot. This approach might give users a direct impression of the relationship between the robots. On the other hand, metaphor is a contextual inheritance from virtual- to visible-type robots. The visible-type robot utilizes a metaphor in his advice about the topic that the virtual-type robot and its user previously discussed so that the user can notice the relationship between the two agents. By utilizing these two different approaches, we believe that the relationship between user and robot will influence the users. We developed a multi-robot healthcare system capable of docking as well as advising with metaphors. The effects of the two approaches were experimentally confirmed.

2 Related Works and Contributions

Previous research on communication robots revealed their capability of naturally communicating with users by utilizing gesture expressions and voice utterances [2], [3]. These are crucial because healthcare system users include people without specialized computing and engineering knowledge. Our research aims to effectively use these robot gestures and utterances for healthcare persuasion. On the other hand, previous research exists on healthcare robot systems [4], [5]. The following are the differences between these studies and ours. First, our targets are healthy subjects living normal lives. Second, we focused on the persuasion of users, not the physical

capability to support them. Concerning the robot's persuasion, several studies have addressed making human decisions. Shinozawa et al. revealed the differences between screen agents and robots agents for recommendations of subject decision making [6]. However, these studies discussed the effects of a single robot or a computer agent but didn't discuss the effects when agents collaborate. The following are the unique points of our research. First, it focused on the effects when two different types of robots collaborate while maintaining their consistency. Second, we set up a concrete purpose--the persuasion of healthy subjects about healthcare matters--in the system to analyze the problem more deeply through a case study.

3 Persuasion Utilizing Docking and Metaphor

Persuasion about healthcare matters is not simple. Previous studies of health behavior theory revealed several necessary steps and methods before people permanently change their healthcare behavior [7]. Our study has been tackling the problems step by step. The goal of our current study is to persuade people to change their awareness of daily health habits. There are several stages before people change their healthcare behavior [8]. The first is to change their awareness of their habits. The second is to prepare and to plan their actions. The third is actual action toward their health. The final stage is to permanently maintain the action. Our study motivates users to take the step forward to the first stage. To tackle this problem, we first focused on robot credibility. According to the theory of trans-theoretical model of health behavior change [8], counselors must constantly give information of the merits and the undone-risks of healthcare behaviors in the first stage. To make subjects listen to the information and to motivate them to change their behavior, robots require feasible credibility. As described above, credibility consists of two different dimensional spaces, authoritativeness and believability. The sense of authoritativeness might be improved by appearances, awards, and job titles. On the other hand, the sense of believability might be improved by making the subject identify with the source. One of the most credible sources in our life is a close friend who is also an expert in an area of interest. In this research, our strategy is to make subjects identify with the robot by utilizing a virtual-type robot and persuading them utilizing a visible-type robot counseling with specialized knowledge. By inheriting the close relationship with the user, we believe that the visible-type robot can persuade users with believability as well as authoritativeness. To make the relationship between user and robot influence the users, we proposed two different approaches, docking and metaphor. Detailed explanations of each approach follow.

3.1 Docking --Physical Approach to Keep Consistency among Robots

Docking is a user action that physically connects virtual-type robots with visible-type robots. At the connection timing, a message appears on the virtual-type robot's screen so that the subject can recognize the virtual-type robot that is controlling the visible-type robot. At the same time, the visible-type robot is activated. The aim of docking is to make subjects feel the inheritance of the relationship from virtual- to visible-type robots. The docking concept is based on the ITACO project [9]. Ogawa et al.

developed a screen agent that could jump from one screen into the other object. They revealed that relationships with certain agents could be inherited by the other when they manage appropriate timing animation and voice effects. The docking effect is designed to directly achieve this effect between virtual- and visible-type robots.

3.2 Metaphor –Contextual Approach to Manage Similarity and Inheritance

In the Metaphor approach, visible-type robots utilize metaphors to persuade the subject on the same topics that the subject shared with the virtual-type robot. In our research, we utilize the ranks of musicians, baseball players, and politicians to express the level of the subject's health. For example, if the subject's daily habit is quite deleterious and the shared topic is baseball players, the visible-type robot might express the subject's daily habit and persuade by saying, "your habit is a minor league baseball team level, and you strongly need to improve your daily habits." There are two aims for adopting the metaphor approach. The first is to make the subject identify with the visible-type robot, which might happen by utilizing the same topic shared with the virtual-type robot. The second is to manage the consistency between the visible- and virtual-type robots. The continuous usage of topics could possibly associate the visible-type robot with the virtual-type robot in subject recognition.

4 Multi-robot Healthcare System

To verify the effects of our two proposed approaches, we developed a multi-robot healthcare system (Fig. 2) to provide users with healthcare information by utilizing gestures, utterances, and images. As shown in Fig. 2, the multi-robot system consists

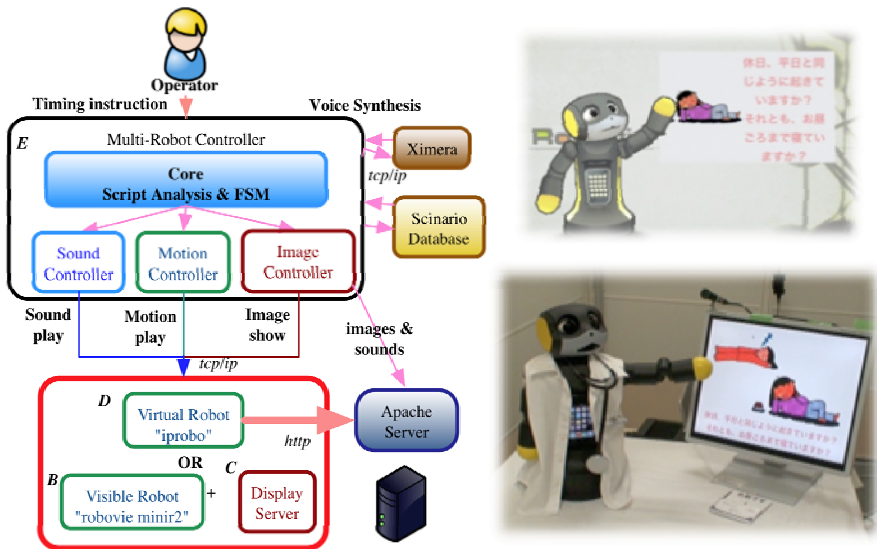


Fig. 2. The Developed System. Left: System configuration. Right-up: iprobo. Right-down: robovie mR2 with display server.

of virtual- and visible-type robots and its controller. The controller controls the virtual- and visible-type robots based on pre-inputted scenarios. The operator manages the timing of their behavior so that the robots can give users properly timed healthcare information. Each robot voice is generated artificially by utilizing “XIMERA,” a voice synthesis system [10], so that the voices of the two robots are identical. The visible-type robot, “Robovie mR2,” stands on a table (See Fig. 2). It is 30-cm tall with a 15-cm radius. It has a 3-degree of freedom (DOF) head, 2-DOF eyes, 1-DOF lids, 4-DOF hands, and 1-DOF body movement. In the experiment, the robot wore a lab-coat and a stethoscope to enhance its authoritative appearance. The display server is a simple server that renders images. The local path of an image file is instructed and the server renders it at the timing of the capturing instruction. The virtual-type robot, “iprobo,” works by iPod touch (Fig. 2) controlled via Ethernet. It can output gestures and utterances while displaying an image beside it. It expresses motions with a combination of sixteen body motions and seven head motions. The role of the virtual-type robot is the same as the combination of Robovie mR2 and a display server. It is singularly capable of presentation by gestures and utterances and images rendered beside the robot.

4.1 Developed Docking and Metaphor Approach

The docking effect is managed by utilizing the developed multi-robot system shown in Fig. 3. The virtual-type robot can detect the status of the power supply from the connector so that it can render the docking animation on the virtual-type robot and control the activation behavior on the visible-type robot at proper connection timings. A scene of the developed docking and the rendered animation is shown in Fig. 3.

On the other hand, the metaphor utilized by the robot was implemented in the robot scenarios in the database. The topic selected by the user was stored in the multi-robot controller, which utilized the topic in the persuasion when controlling the visible-type robot. The metaphors and topics were pre-inputted before the experiment.

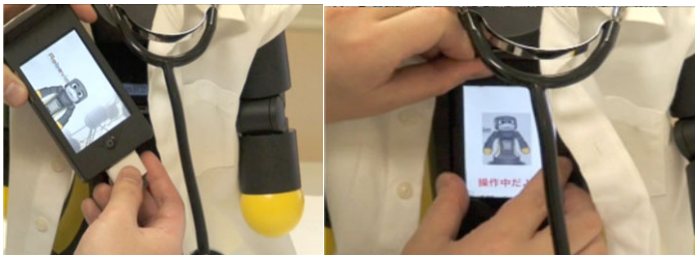


Fig. 3. The developed docking (left: at the connection, right: connecting animation comes up)

5 Experiment

To verify the effectiveness of the proposed approaches, we conducted an experiment with the developed system. The experiment is a WOZ style with two participants: a subject and an operator. The subject communicated with the robot and evaluated the multi-robot healthcare system. The operator explained the experiment and controlled the robots in the implemented multi-robot system.

5.1 Experimental Environment

The experimental environment is shown in Fig. 4. It consists of two different interaction spaces, Interactions 1 and 2 (circles in Fig. 4). Interaction 1 is where interaction is done with the virtual-type robot. On the other hand, Interaction 2 is where interaction is done with the visible-type robot and the display server. The Interaction 2 space is designed as a separate room to evoke the atmosphere of a doctor's office.

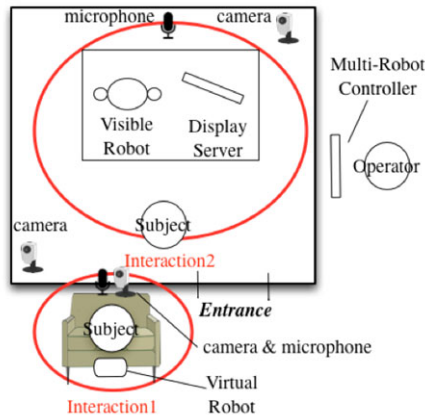


Fig. 4. Experimental environment

In the environment, there were three cameras and two microphones with which the operator could observe subject reactions and control the robots at proper times (Fig. 6). The experimental subjects were 22 university students (8 males and 14 females). The experiment consisted of two different types of tasks: 1 and 2. The detail of each task follows:

1. Task 1

The subject interacted with the virtual-type robot to create a shared topic by playing a simple word-guessing game with the robot. A) First, the subject chose a topic for the game from musicians, baseball players, and politicians. B) The subject and the robot guessed the names of the selected topics one by one. C) The loser is the one who fails to remember the name of the topic or repeated a name that had already been called. The robot has 10 name candidates in each topic and called the names after the subject. The robot also gave sympathetic comments randomly to the subjects such as “I was just going to say that word.” or “Cool choice.”

2. Task 2

From the virtual-type robot, the subject received counseling that is separated into four stages: informed, evaluated, persuaded, and concluded. Detailed steps of each stage are shown in Table 1.

Table 1. Counseling stages of the experiment

Stages	Stage Contents
Informed stage	Robot asked four questions about subject’s daily habits. Subject answered them one by one. After subject answers, it gives healthcare information about question.
Evaluated stage	Robot evaluated subject’s daily habits into three levels: Bad, Not too bad, Good; these were changed by experimental condition (See condition section).
Persuaded stage	Robot persuaded subject to improve daily habits and advised subject about the healthcare behaviors that depend on answers in informed state. At the same time, it explained the risks if subject did not follow the advice.
Concluded stage	Robot asked subject to reflect on daily habits again. At the last, robot thanked subject for listening and said counseling was over.

There are three conditions in the experiment: no docking and no metaphor, metaphor only, and docking and metaphor. Within metaphor only condition, robot utilized a metaphor to evaluate subject’s daily habits concerning topic in word-guessing game (See Table 2). Within docking and metaphor condition, operator asked subject to connect virtual-type robot to visible-type robot so that subject could experience docking effects, while the robot utilized metaphor. Within no docking and no metaphor, none of them were given. The numbers of the subjects for each condition were eight for no docking and no metaphor, eight for metaphor only, and six for docking and metaphor.

Table 2. Robot’s evaluation utilizing metaphor

Topics	Bad	Not too bad	Good
Musician	Group activity level	Indie label level	Professional debut level
Baseball Player	Amateur baseball level	Benchwarmer level	Professional player level
Politician	Congressional chauffeur level	Congressional secretary level	Congressman level

5.2 Evaluation

This experiment was a between subject design. In the experiment, subjects evaluated their interactions with the robot by answering questionnaires that consisted of two different scales, Source Credibility and the Relational Communication Scale [11]. Source Credibility (SC) measures multi-dimensional attitudes about a source [12] and consists of two different dimension scales, authoritative and character. We adopted this scale to measure the system’s authoritative and investigated the relationship between authoritative and the robot’s persuasion. On the other hand, the Relational Communication Scale (RCS) measures interpersonal relationships among people [13] and consists of eight different dimensional scales, seven of which we adopted (the remaining scale was not suitable). Each RCS scale consists of three or four questions, and average scores are utilized for evaluation. With this measure, we

investigated the relationship between interpersonal relationships and the robot's persuasion. Additionally, we asked the subjects these questions: 1) was your awareness of healthcare behavior encouraged by the interaction?; 2) do you plan to heed the robot's advice? These questions confirmed the effect of the robots' persuasion. All were evaluated on a semantic differential scale (1-7 grades). A value over 4.0 means the subjects positively evaluated the scale. The opposite means that the subject negatively evaluated the scale. The questionnaire was asked randomly to make them counter-balanced.

5.3 Results

The experimental results are shown in Tables 3 and 4. Table 3 shows the scores of the questionnaire items, 1), 2). Table 4 shows the correlations between the dimensional scale scores of SC and RCS and the score about heeding the robot's advice. The correlation values showed the scales on which the subjects placed an emphasis when they decided to heed a robot advice. The higher the value was, the more the subjects placed an emphasis on the scale.

Table 3. Means and S.D.s of questionnaire for persuasion and consistency

Questionnaire	No Docking, No Metaphor	Metaphor Only	Docking and Metaphor
Awareness	6.25 (0.82)	5.37 (1.40)	6.00 (1.00)
Heeding Advice	6.25 (1.05)	5.12 (1.39)	5.00 (0.75)

Means (S.D.s) of scores corresponding to questionnaires. No significant differences with ANOVA.

Table 4. Correlations between scores of each dimensional scale and the scores of heeding advice

Measures	Source Credibility		Relational Communication Scale				
	Authoritativeness	Character	Similarity/Depth	Immediacy/Affection	Receptivity/Trust	Dominance	Equality
No Docking No Metaphor	0.71	0.78	-0.26	0.77	0.59	-0.05	0.59
Metaphor Only	0.60	0.89	0.58	0.71	0.71	0.17	0.70
Docking and Metaphor	-0.41	-0.14	0.40	-0.06	0.21	0.81	0.48

Formality and Composure in RCS are omitted, because there were no clear correlations.

According to Table 3, there were no significant differences in questionnaire scores of 1 and 2 among the conditions. The mean scores of awareness of the healthcare behavior and heeding the robot's advice were over 5.0, revealing that the subjects had positive impressions of the robot's persuasion scenario. Still there was difference between *no metaphor and no docking* condition and the others. This is due to the fact that there were few subjects evaluated the scale lower by an unexpected personal reason (e.g. One of the subject answered in the free-form that it is quite hard for me to

decrease drinking parties at all.) When we omit the score evaluated lower by personal reason, the score of heeding advice in *metaphor only* condition comes up to 5.42, while that of *metaphor and docking* condition comes up to 5.60.

According to Table 4 (In our research, if the correlation value exceeds 0.70, the scales are considered correlated clearly. Correlation values over 0.70 are underlined in Table 4.), there were clear correlations between the scores of heeding the robot's advice and authoritativeness, character, and immediacy/affection in the no docking and no metaphor condition. On the other hand, there were clear correlations between the scores of heeding the robot's advice and the scores of character, immediacy/affection, receptivity/trust and equality in the metaphor only condition. Based on these differences, we confirmed that the subjects tended to emphasize interpersonal relationships (immediacy/affection, receptivity/trust and equality) when the robot utilized the metaphor approach, and if there were no approaches, they tend to emphasize source credibility scales (authoritativeness and character). These changes support our thesis that the inheritance of human-robot relationship could affect the robot persuasion. As for the docking and metaphor condition, there was correlation with the dominance scale. Dominance scale is the scale to measure the subject feeling of the robot dominating conversation. The score was evaluated with the sentence, such as "The robot attempted to persuade me." This means that the more the subject felt the robot was aggressive to persuade him / her, the more they decided to heed its advice. We formed several hypotheses to explain this result. The first one was, of course, the results were due to the relational inheritance. However, if they were due to the relational inheritance, the other RCS scales should also have correlations with the scores of heading advice. The other hypothesis was that the docking sequence has the effect of a foot-in-the-door technique. Because the operator asked the subjects to connect the virtual to the visible and the subjects followed the request once, they might feel easy to heed the robot's request. This is not directly due to the relational inheritance. But still the results indicate us an interesting effects of the proposed docking approach for persuading users. Confirming the effectiveness of docking more in details will be the future work with a larger number of the subjects. We are also planning to conduct an experiment with a docking-only condition for confirming a single docking effect.

6 Conclusion

We proposed two different approaches for a multi-robot healthcare system: docking and metaphor. They are used for inheriting the consistency of visible- and virtual-type robots and making subjects identify with them. This research examined the effects of the two approaches on user persuasion. We developed a multi-robot healthcare system that persuades subjects to change their daily healthcare habits based on our proposed two approaches. Through an experiment to verify the effects of the approaches, we revealed the followings:

1. By utilizing the metaphor approach, subjects emphasized interpersonal relationships with the robots when they decided to heed their advice.
2. With the developed docking effect, the subjects emphasized the robot's aggressiveness when they decided to heed their advice.

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State Representation with Perceptual Constancy Based on Active Motion

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Abstract. In a robot system, it is important to consider how the outside environment is expressed as a state using sensor information. In this study, we provide a state representation that can express the sensor output changed by environmental change as the same state. It assumes that sensor outputs are probability distributions, and the distances between the distributions of each sensor's output are used to express a state. To confirm the effectiveness of the proposed state representation, we conducted experiments using a mobile robot. The results confirmed that the proposed representation could recognize similar states using a converted sensor output.

1 Introduction

Over the past few decades, many studies have been conducted on autonomous robots. The relation between a robot and an external environment is expressed as a state using sensor information. Then, the robot generates behavior based on a mapping between the state and their actions. Concern regarding a robot's adaptability to various environments has been growing.

How is the external world expressed as a state? This issue of state representation depends on a robot's environment and context. For example, consider a mobile robot that uses a camera as a sensor and is in an environment where lighting conditions change. In this environment, even if the robot is in the same position and posture (called a situation), the information from the camera differs with lighting conditions. When the robot's task depends on lighting conditions, it must recognize changes in lighting. For this purpose, the state should be able to express the difference in lighting conditions. On the other hand, when the robot's task does not depend on lighting conditions, the robot uses the same mapping between a state and an action even under different lighting conditions, and thus should recognize different lighting conditions as the same state. This

paper provides a state representation that can express the sensor output changed by environmental change as the same state.

We define the sensor information observed from environment A as z_A . Let us assume that z_A is converted to $z_B = g(z_A)$ by an environmental change from A to B . Note that the situations in each environment are the same. In the example described above, transform g corresponds to the effect of a change in lighting conditions. If information on g is known, it is easy to express z_A and z_B as the same state. However, using such prior knowledge for conversion is difficult in a new environment. Moreover, although the use of a state, which is assumed in advance by a designer, that is invariant to environmental change has also been proposed [1], it cannot be applied to unexpected environmental change.

Human perception has a feature called constancy. Perceptual constancy is the tendency to perceive an object's qualities as constant under changing angle of perspective, distance, or lighting conditions. For example, we recognize a board as rectangular although different trapezoidal images of it are reflected on the retina depending on viewpoint. In this instance, perceptual constancy allows us to recognize the same object from different visual stimuli.

J. J. Gibson [2] argued that constancy is not based on prior knowledge. (Prior knowledge consists of the form of the rectangle seen from various viewpoints, memorized in advance on the basis of precedent.) Gibson claimed that the active motion of an observer plays an important role in constancy. He stated that the observer has extracted the unchanging features (invariants) of an object from the changing pattern of stimuli produced by the observer's motion. The results of the dynamic touch experiments of M. T. Turvey supports Gibson's argument [3]. In this study, we propose a state representation that uses the robot's own motion to create perceptual constancy.

Several studies have examined the perceptual systems of a robot based on the robot's own motion [4,5]. In these studies, the state was expressed using change in the visual information produced by motion of the robot itself. The change in visual information is less affected by environmental changes, such as lighting conditions. The researchers proposed a state representation using optical flow and performed an obstacle-avoidance task with a mobile robot. However, these studies did not verify whether a robot can generate suitable behaviors using the same state-action mapping before and after an environmental change. We have proposed a state representation using a distance sensor [6], wherein the state is expressed using the change in distance sensor output produced by the robot's own motion. The paper confirmed that the robot could perform a wall-following task even if the environment changed. However, this method applies only to environmental changes in which transform g is expressed by parallel translation.

This paper presents a state representation that can be applied to more general environmental changes g . It assumes that sensor outputs are probability distributions, and the distances between the distributions of each sensor's output are used to express a state. We confirm the effectiveness of the proposed representation using a mobile robot with distance sensors.

The rest of the paper is organized as follows. Section 2 describes the proposed state representation. Section 3 presents experimental results and discussion and finally Section 4 concludes with a summary and outlines future work.

2 Proposed State Representation and Its Application to Behavior Learning

In this section, we will outline our state representation and explain how to apply this to a mobile robot. Finally, we will describe behavior learning by reinforcement learning.

2.1 Outline of Proposed State Representation

Information and statistical theory use many measures and divergences that express the distance between two distributions. The f -divergence (f -div.) is a family of measures introduced by Csiszár and Shields [7]; the well-known K-L divergence belongs to this family. The f -div. of a distribution $p_i(x)$ from $p_j(x)$ is defined by

$$f_{div}(p_i(x), p_j(x)) = \int p_j(x) f\left(\frac{p_i(x)}{p_j(x)}\right) dx, \quad (1)$$

where $f(y)$ is a convex function defined for $y > 0$, and $f(1) = 0$.

Qiao and Minematsu have proposed that the f -div. is invariant to invertible transforms, and they showed that all the invariant measures must be written in the form of the f -div. [8]. Further, they applied the invariant of measures to speech recognition [9].

In this study, we use the invariant of the f -div. to propose a state representation. The sensor outputs are assumed to be probability distributions, and the f -div. of the sensor outputs z_A and $z_{A'}$ observed under the same environment is set to $f_{div}(z_A, z_{A'})$. The environmental changes z_A and $z_{A'}$ are transformed to z_B and $z_{B'}$, respectively. If z_B and $z_{B'}$ are described as $z_B = g(z_A)$ and $z_{B'} = g(z_{A'})$, and if g is an invertible transform, then $f_{div}(z_A, z_{A'})$ is equal to $f_{div}(z_B, z_{B'})$.

In a previous study [10], we used invariant measures for state representation. The state is expressed as the distance between two sensor outputs (distributions) observed at two different postures. It has been shown that a similar state is acquired from different outputs observed under a different environment. However, in this method, the robot must remain for a definite period in the same posture to observe the sensor output. To solve this problem, in this paper, we use the sensor output observed while a robot is in motion. The proposed method will achieve smooth action generation.

2.2 Proposed State Representation and Its Application on a Mobile Robot

In this subsection, we propose a state representation using the distance between two distributions and explain its application on a mobile robot. Figure 1 shows

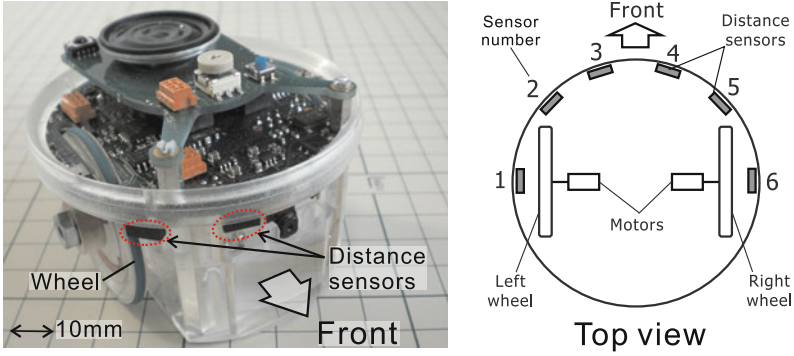


Fig. 1. Autonomous mobile robot e-puck and its infrared distance sensors

the autonomous mobile robot called e-puck [11], which is used in the experiment described in the next section.

The robot has eight infrared distance sensors. We used only the six sensors indicated in Figure 1 in the experiment. Figure 2 shows how the state representation is acquired. First, while a robot moves in time Δt , M sensor output is memorized for every sensor.

Then, the distances between the distributions of each sensor's output are calculated. In this study, the distribution of sensor i ($1, \dots, i, \dots, I$) is assumed to be Gaussian with mean μ_i and variance σ_i . We used the Bhattacharyya distance (BD) as the distance between two distributions. The BD is a function of f -div. The BD between the output distributions of sensor i and j (p_i and p_j) is given by the following formula.

$$BD(p_i, p_j) = \frac{1}{4} \frac{(\mu_i - \mu_j)^2}{\sigma_i^2 + \sigma_j^2} + \frac{1}{2} \ln \frac{\sigma_i^2 + \sigma_j^2}{2\sigma_i^2\sigma_j^2} \quad (2)$$

The BD is calculated from the sensor output distributions acquired while the robot is in motion from time $t - \Delta t$ to t . Then, the vector of which the distances are components is called the state vector at time t and is defined as follows.

$$\mathbf{v} = (v_{1,2}, v_{1,3}, v_{1,4}, v_{1,5}, v_{1,6}, v_{2,3}, v_{2,4}, v_{2,5}, v_{2,6}, v_{3,4}, v_{3,5}, v_{3,6}, v_{4,5}, v_{4,6}, v_{5,6}) \quad (3)$$

Here, $v_{i,j}$ is $BD(p_i, p_j)$. In this method, when an object is outside the sensing range of a sensor and the distribution is 0, the distance between distributions cannot be calculated. In such a situation, the distance between the distributions of that sensor and the other sensors is set to 0.

2.3 Behavior Learning

In this subsection, we explain behavior learning in the robot using reinforcement learning [12]. Although reinforcement learning does not require prior knowledge

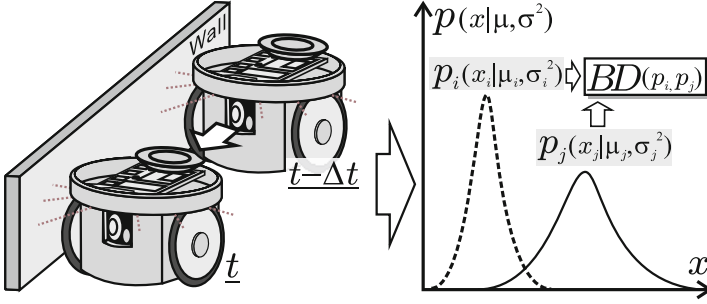


Fig. 2. Proposed state representation using e-puck

about a robot and environment, when a robot acts by trial and error, it can autonomously gain a suitable state-action mapping.

For the behavior learning, we apply Q -learning, which is a reinforcement learning algorithm, and it requires a discrete state and action. We use a self-organized map (SOM [13]) for state discretization. The SOM is a well-known neural network model. By unsupervised learning using learning vectors, a SOM can classify its input. We trained a SOM using many state vectors as learning vectors. After training, when a state vector is input to the SOM, it outputs the index n ($1, \dots, n, \dots, N$) of the class in which the vector was classified. N is the number of neurons that constitute the SOM.

The Q -learning algorithm [14] updates the Q -value $Q(s, a)$, which is assigned to each state-action pair. $Q(s, a)$ is an evaluation of action $a \in A$ in state $s \in S$. The updating of the Q -value in the algorithm is given as follows.

$$Q(s_t, a_t) \leftarrow (1 - \alpha)Q(s_t, a_t) + \alpha \left\{ r_{t+\Delta t} + \gamma \max_{a' \in A} Q(s_{t+\Delta t}, a') \right\} \quad (4)$$

Here, s_t and a_t are the state and action, respectively, at time t ; r_t is the received reward for executing a_t in s_t . $s_{t+\Delta t}$ is the new state, and $\gamma \in [0, 1]$ and $\alpha \in (0, 1]$ are the discount rate and learning rate, respectively.

Even if a robot takes the same action a in the same state s , depending on the dispersion of a state, the state either remains the same or changes to another state. Therefore, one state transition does not correspond to a single action. To address this problem, called state-action deviation [15], the Q -value is updated by equation (4) only when the state changes to a different state.

3 Experimental Results and Discussion

In this section, we describe mobile robot simulations. We confirm the effectiveness of the proposed state representation through behavior learning of the mobile robot. First, the robot executed behavior learning and obtained the state-action mapping. After the learning, we transformed the sensor output artificially and verified whether the robot could perform a task using the obtained mapping.

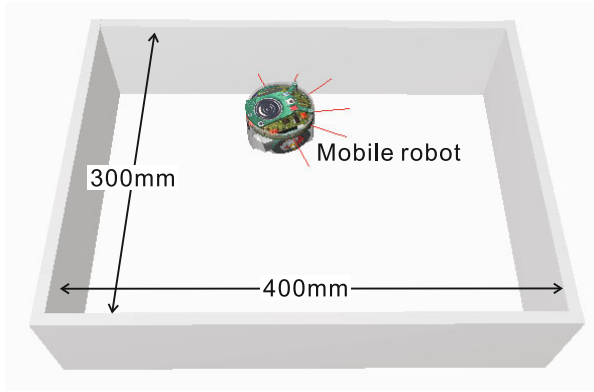


Fig. 3. Experimental environment

3.1 Simulation Setup

We used a mobile robot with six distance sensors and two wheels; all the sensors had the same specifications. The detection range of the sensors was 40 mm. The actual range of distance sensor readings was 0-3600, where 3600 indicates that the robot was very close to an object, and 0 indicates that there was no object within the sensor's detection range. We defined the output of sensor number i at time t as $o_{t,i}$. The simulated behaviors of the robot were moving straight, turning left, and turning right; the corresponding motor commands were defined as m_f , m_l and m_r , respectively.

In the experiment, we first acquired the learning vectors for the SOM. The robot was then set in the experimental environment (figure 3) and moved in response to motor commands selected randomly for a period Δt . We acquired 500 learning vectors by repeatedly performing the above mentioned actions, and then we used these vectors to train the SOM. The number of neurons in the SOM is $N = 100$, and $\Delta t = 0.6$ sec. A wall-following task was used for investigating the behavior learning. When all the following conditions were satisfied at time t , the reward r_t was set to 10; otherwise, it was set to -1.

- 1) $o_{t,2} < 1080$ and $o_{t,5} < 1080$
- 2) $o_{t,1} > 0$ or $o_{t,6} > 0$
- 3) The motor command is m_f

The learning time is 10,000 steps (one step= Δt). The robot was placed near the wall every 500 steps during learning. The discount rate γ was 0.9. The learning rate α was initially set to 1 and gradually changed to 0. The number of the acquired sensor output M was 20.

Figure 4 shows the acquired reward. The reward is the average of five learning episodes (10,000 iterations times 5). Figure 5 is a snapshot of the behavior of the robot after learning. These results indicate that the behavior learning was successful.

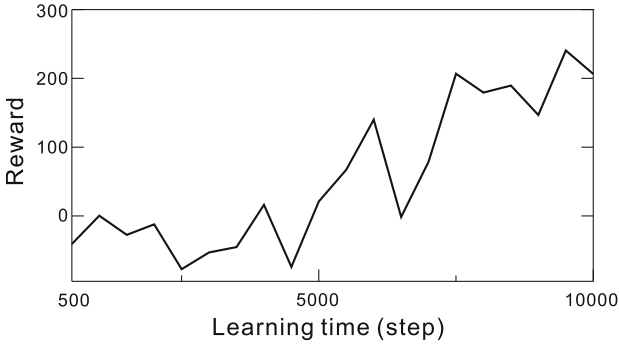


Fig. 4. Reward taking average of five learning episodes

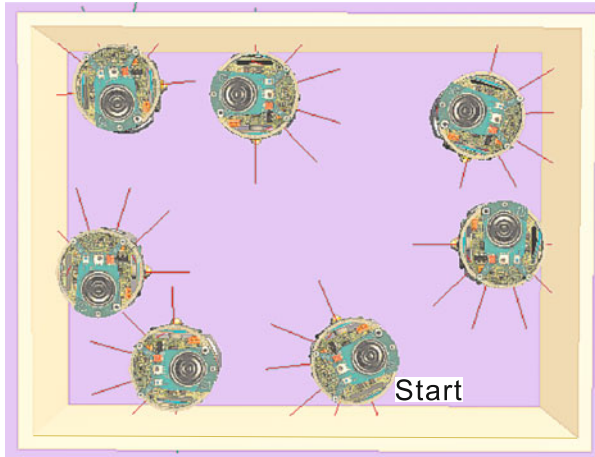


Fig. 5. Snapshots of the mobile robot (wall-following)

3.2 Results

The sensor readings of the robot after behavior learning are converted as follows.

$$o'_{t,i} = bo_{t,i} + c \quad (i = 1 \sim 6) \tag{5}$$

Here, $o'_{t,i}$ is the converted sensor output, and b and c are a linear transformation and shift, respectively. We confirmed the robot’s performance by examining the converted sensor readings. Table 6 shows the obtained reward for each b and c . These rewards are the total for 500 steps; they are normalized by the total rewards obtained by the robot with normal sensor readings.

For comparison, we executed the same experiment using different state representations (type 1 and type 2). In type 1, the state is expressed by the difference

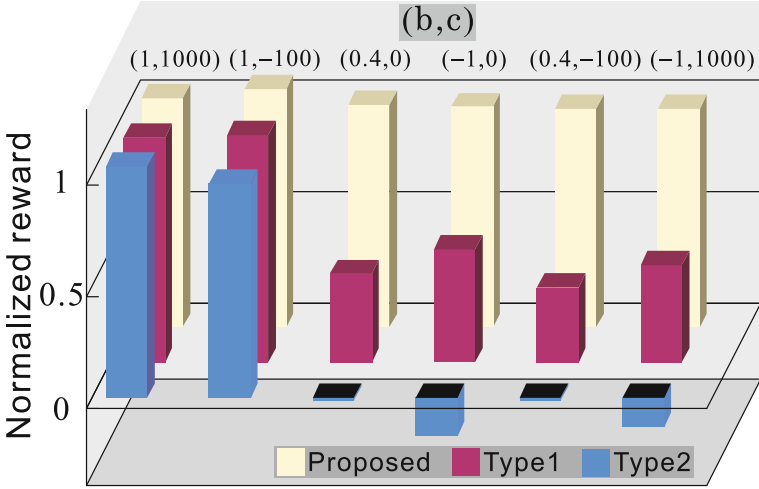


Fig. 6. Performance in terms of converted sensor output (normalized reward)

in sensor output over a short time (Δt) [6]. The state vector of type 1 is defined as follows.

$$\mathbf{v}_{type1} = (v_{d,1}, \dots, v_{d,6}), \quad v_{d,i} = o_{t,i} - o_{t-\Delta t,i} \quad (6)$$

In type 2, the state vector is defined as follows.

$$\mathbf{v}_{type1} = (v_{1,2}, v_{1,3}, v_{1,4}, v_{1,5}, v_{1,6}, v_{2,3}, v_{2,4}, v_{2,5}, v_{2,6}, \\ v_{3,4}, v_{3,5}, v_{3,6}, v_{4,5}, v_{4,6}, v_{5,6}) \quad (7)$$

Here, $v_{i,j} = o_{t,i} - o_{t,j}$.

The same parameters were used as in the first experiment described above. We confirmed that robots with state representations of types 1 and 2 can perform the wall-following task after behavior learning.

In figure 6, when the conversion is a shift, the robots with the proposed state representation and state expressions type 1 and type 2 can perform the task as satisfactorily as the robot using untransformed sensor output. However, the performance of the robot using the state expressions degrades sharply to a linear transformation ($b \neq 1$). On the other hand, the performance of the robot using the proposed state representation barely degrades. These results indicate that the proposed representation is not affected by changes in the information from the sensors.

3.3 Discussions

We confirmed that the accuracy with which the output distribution is estimated has a considerable effect on the proposed state representation. Thus, the way that the robot's action and Δt are set up is important. In this study, the robot's

action is set up in advance by the designer. The robot's action is not necessarily optimal because of perceptual constancy. The action by which the robot fits itself for perceptual constancy must be generated according to the environment. The proposal of a mechanism by which the action for constancy is produced spontaneously will be studied in the future.

In general, two perceptual systems are required for a robot: one which is not affected by environmental changes, such as the proposed state expression, and one that recognizes environmental change. For the adaptability a robot, it is important that the functions of these systems complement each other. In the future, we will combine the two systems and propose a mechanism that dynamically chooses the optimal result from the systems according to the environment and task.

4 Conclusions

This study provides a state representation that can express the sensor output changed by environmental change as the same state. It assumes that sensor outputs are probability distributions, and the distances (f -div.) between the distributions of each sensor's output are used to express a state. The proposed representation is based on a change in distance sensor output produced by robot's own motion. This state representation is based on the fundamental mechanism of perceptual constancy. We applied it to an autonomous mobile robot with distance sensors, and the robot learned suitable behavior (a state-action map) for a wall-following task by reinforcement learning. After the learning, we confirmed that the robot can perform the same task using the same map despite having converted the sensors' output.

In the future, verification experiments using various kinds of robots and sensors will be needed to confirm the universality of the proposed state representation.

Acknowledgment

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Selection of Actions for an Autonomous Social Robot

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Abstract. Autonomy is a prime issue on robotics field and it is closely related to decision making. Last researches on decision making for social robots are focused on imitating humans' mind for taking decisions. Following this approach, we propose a motivational system for decision making using internal (drives) and external stimuli for choosing the right action. Actions will be selected from a finite set of skills in order to keep robot's needs within an acceptable range.

We present how our motivational decision making is applied to a social robot showing an improvement in robot's autonomy.

Keywords: motivations, decision-making, autonomy, social robot.

1 Introduction

Social Robots are intended for interacting with humans and assisting them in several tasks. During these tasks, it is desired that robots are able to accomplish such task by themselves without no surveillance. This idea implies a certain level of autonomy.

Autonomy is a term widely used in literature and its meaning ranges from very different values. [7] refers autonomy as *systems capable of operating in the real-world environment without any form of external control for extended periods of time*. But is it possible to achieve a full autonomous robot? Is it desirable? Absolutely autonomous robots are impossible to build. Robots are designed for achieving duties and it implies some kind of interaction with the world. Even human beings do not have this level of autonomy, they depend on others and their environment.

Some definitions of robots classify them as a especial kind of agents and being an agent entails making choices [14]. Consequently robots have to be endowed with some kind of decision making. We consider level of autonomy of robots as the amount of decisional mechanisms they are endowed with [11].

In this work we propose a motivational system for autonomous decision making which endows robots with the capacity to decide what to do and when to do it for satisfying its inner needs.

The rest of the paper is organized as follows. Next section presents some previous works about autonomy in robots and decision making. After that, our

theoretical approach is explained and then how it has been implemented in a real platform will be shown. Finally conclusions are summarized.

2 Autonomy in Robots

Autonomy and more precisely autonomous robots have been extensively studied in the last years. More general researches have been focused on autonomous agents. As it is said at [2], agent autonomy is defined like the capability to interact independently, exhibiting control over its own internal state. In addition, [31] mentioned that autonomy is the degree in which one agent is independent with respect to another entity, the environment, other agents or even its own developer. Additionally, [3] consider autonomy as a measure and adjustable value.

Regarding robots, [1] and [10] present autonomy in robots as the capacity of producing plans for reaching a given goal. These plans could be modified on the fly and goals are given by users. At [13] adaptive autonomy is implemented in a tele-operation robot and the change in autonomy level is made dynamically.

As it has been mentioned before, autonomy in robots is very close to decision making. Different approaches have been used for decision making in robots. [28] implemented fuzzy decision making for navigation purposes in a robot. In contrast, [26] makes decisions computing goals priorities based on its importance and its urgency. Schermerhorn also remarks the importance of dynamic autonomy in the performance of a robot team. Schetz [27] presents a decision making using likelihood of success, the benefit and the cost of an action. In [15], decisions are taken considering information gathered by humans and robots and operators are treated as perceptual resources of information; operators are queried depending of the amount of uncertainty in robot's beliefs.

As in many others scientific fields, researches try to imitate humans' brain and last investigations emulate humans' decision making. Accordingly, emotional and motivational models are suggested. As it has been exposed at [6], humans' decision-making is not affected only by the possible outcomes, but also emotions play a main role. Emotions are applied as a biases mechanism for decision-making [30]. In view of it, other authors propose decision making systems based on motivations and drives. In this work, we follow this approach too where no specific goals are defined. Other motivational decision making system is proposed at [21] where selected actions depends on the behavioral state.

3 Our Approach

We proposed a decision making system based on motivations where no specific goals are given in advance; the objective of its life is to *survive* and to be *happy*, just as you and me.

In our decision making system the autonomous robot has certain needs (drives) and motivations. The goal is to keep these needs within an acceptable range. For the purpose of it, the system will generate goals (behaviors or actions) taking into account the state of the robot. The state of the robot is composed by internal state and external state. The process will be as follows:

1. Determine the internal state
2. Determine the external state
3. Choose the right action

Following, these steps will be explained.

The robot can be parametrized by several variables, which must be at an ideal level. When the value of these variables differs from the ideal one, an error signal occurs: the drive. These drives constitute urges to act based on bodily needs related to self-sufficiency and survival [9]. In this approach, the drives are considered as the internal needs of the agent.

Motivations are those internal factors, rather than external ones, that urge the organism to take action [25]. The motivational states represent tendencies to behave in particular ways as a consequence of internal (drives) and external (incentive stimuli) factors [12]. In other words, the motivational state is a tendency to correct the error, i.e., the drive, through the execution of behaviours.

In order to model the motivations of the agent, we use Lorentz's hydraulic model of motivation as an inspiration [16]. In Lorentz's model, the internal drive strength interacts with the external stimulus strength. If the drive is low, then a strong stimulus is needed to trigger a motivated behaviour. If the drive is high, then a mild stimulus is sufficient [8]. Therefore, the intensities of the motivations are calculated as shown in (1)

$$\begin{aligned} \text{If } D_i < L_d \text{ then } M_i &= 0 \\ \text{If } D_i \geq L_d \text{ then } M_i &= D_i + w_i \end{aligned} \quad (1)$$

where M_i are the motivations, D_i are the related drives, w_i are the related external stimuli, and L_d is called the activation level. Motivations whose drives are below respective activation levels will not compete for being the dominant motivation. The general idea is that we eat when we are hungry and also when we have food in front of us, although we do not really need it.

Once the intensities of the motivations are calculated, the **internal state** of the robot is determined by the motivation with the highest value. This is the dominant motivation.

Then, the state of the robot in the world, i.e. the external state, has to be established. The world is modelled as objects and states related to them. Therefore the **external state** is defined as the states related to all objects in the world. Accordingly, the external state restricts the possible actions: for example, we can not eat if we do not have food.

The behavior at each moment will depend of the state of the robot (internal and external) and the potential actions. Tuples formed by the state and each action will have an associated value which represent the suitability of that action on that state. These values can be tuned by learning.

Actions affect the world and consequently the robot too. Hence robot's state varies dynamically during robot's lifespan. So actions will be selected accordingly to each configuration of the world.

4 A Decision Making System in Maggie

In this section, a first version of the decision making system is presented and how it interacts with the AD architecture is explained.

The intended decision making system will be developed and implemented on the social robot named Maggie [24] which is controlled by the Automatic-Deliberative (AD) architecture [5] [4]. Because of the lack of space, more detailed information is available in references. Summarizing, AD is a two levels architecture where communication is accomplished by Events, Short Term Memory and Long Term Memory (figure 1). Its essential component is the skill and its located in both levels [22]. An extensive example about how it is applied is presented at [23]. This paper presents how decision making system is added to the AD architecture.

The proposed decision making system has a bidirectional communication with the control architecture of the robot, the AD architecture (figure 1). On the one hand, the decision making system will generate the goal of the robot that may be translated into an action or behaviour. This behaviour will be taken by the AD architecture and the robot will fulfill the goal by activating the corresponding skill (deliberative or automatic one). On the other hand, the decision making system needs information from the environment in order to update the internal state of the robot. This information will be provided by the sensors of the robot.

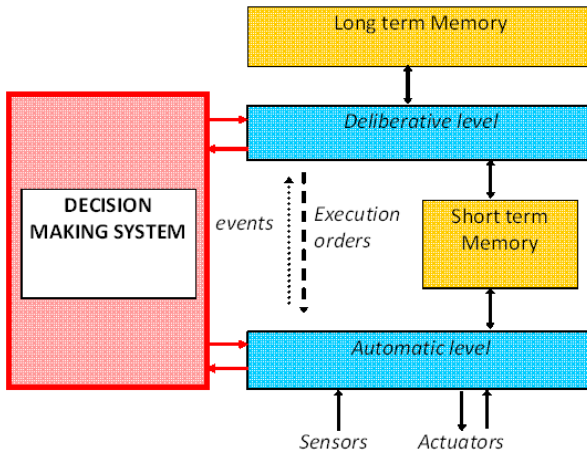


Fig. 1. AD architecture with the decision making system

The aim of the presented decision making system is to achieve a full autonomous robot. Therefore, the most appropriated action at each moment will be selected by the decision making module. Choosing the right action depends on the value of the motivations, previous experiences, and the relationship with the environment. All these elements have been modelled in order to be processed by the implemented decision making module.

The whole process can be summarized in the next steps:

1. Computing the dominant motivation (internal state)
2. Sensing the state in the world (external state)
3. Evaluating possible actions and selecting one of them

Following an example of how to apply our motivational decision making system is presented.

4.1 Internal State: Drives and Motivations

As expressed by equation (II), each motivation is represented by an integer value and it is affected by two factors: internal needs and external stimuli. Internal needs are the drives and their values depend on inner parameters. External stimuli are the objects situated in the environment altering the robot motivations. In addition, each motivation has the activation level: under it, motivations values will be set to zero and hence they will not be considered for the dominant motivation.

As mentioned, the internal needs, the drives, represent an internal value. Each motivation is connected to a drive. The selected drives are:

loneliness: the need of companion.

boredom: the need of "fun" or entertainment.

submissiveness: the need of obeying people orders.

energy: this drive is necessary for survival.

Since we want Maggie to be an autonomous social robot and based on past works and experiences, four non-conventional motivations have been defined:

social: it means the need of interaction with a human and its drive is *loneliness*.

recreational: this motivation is related to entertainment purposes. Its associated drive is *boredom*.

obedience: it is linked to respect others' wills and it is related to submissiveness drive.

survival: it refers to the energy dependence. This motivation is connected to *energy* need.

Since drives temporally evolve from scratch, motivations do as well. In our implementation, *loneliness*, *boredom*, and *submissiveness* drives linearly increase but with different parameters. It means that, as time goes by, these drives become bigger and bigger, and so do the corresponding motivations. *Loneliness* is the fastest drive since boredom and submissiveness evolve slighter. This is because in social robots, as ours, interaction with people is the most relevant aim and hence social motivation takes priority over the others two.

The most relevant inner need, due to the necessity of survival, is the *Energy* drive. If we want to achieve a full autonomous robot, power autonomy is the first step. Therefore, this drive will keep its initial value until a low level battery is detected. Then, its value will suffer a drastic raise becoming the most critical drive.

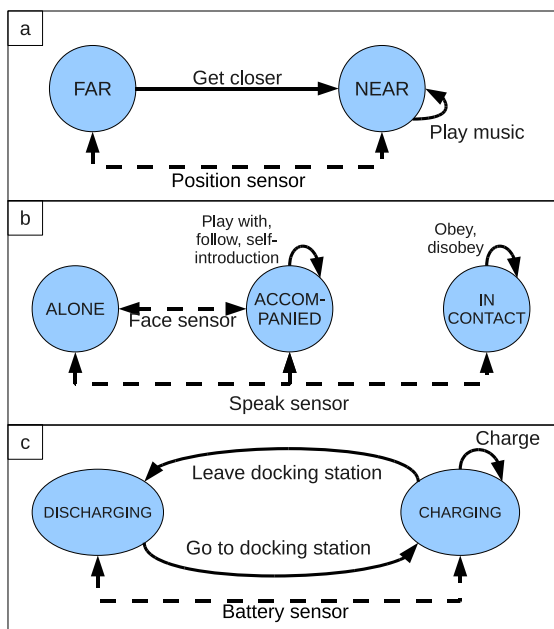


Fig. 2. States and actions for items: (a) TV, (b) person, and (c) docking station

After a drive is satisfied, it does not intermediately start evolving, there is a *satisfaction time* before it evolves again. The same idea occurs to you: once you have eaten, you do not feel hungry but it takes some time before you need to eat again.

4.2 External State: Sensing the World

The world is sensed by the robot in terms of objects and the related states to these objects. Objects are not limited to physical objects but abstract objects too. So, as a first approach, the world where Maggie is living in is limited to the laboratory and three objects have been defined: people living around the robot, a television/radio appliance and the docking station for supplying energy. Also relative states to all these items have to be presented and the transitions from one state to another is detected by several skills running on Maggie. More technical issues about how objects are sensed can be found in the references.

In Figure 2, objects, actions, and transitions from one state to another are shown. Dashed arrows represent skills monitoring the states, continuous ones mean actions executed with the objects, and circles are the states related to each item. If an action does not appear at one state, it means that it is incoherent to execute it from that state, e.g., Maggie cannot *play music* if it is *far* from TV or it cannot *follow* a person if it is *alone*.

External stimuli. Just like human beings can feel thirsty when they see water, the motivations are influenced by objects in the world and their states. That is called the external stimuli for motivations. These stimuli may have more or less influence: their values depend on the states related to the objects. In our implementation, all external stimuli values have been fixed empirically

4.3 Acting in the World: What Does Maggie Do Now?

Maggie interacts with the world through the objects and their potential actions. These actions are implemented as skills in the AD architecture. The actions cause effects over the drives. When the actions have ended, i.e. when the skill associated has been blocked because it has reached its goal, the effects are applied. If an error occurs during a skill execution or it is not successful, this situation is notified and its effect is not applied. In our experiments, most of the effects satisfy the drive, which becomes zero or decreases its value. Actions can also “damage” some drives of the robot increasing their values; i.e. *disobey* action increases *submissiveness* drive.

Next, once the world has been modelled, how the decision making system operates is explained. First of all, when the system starts, drives begin to evolve independently from their initial value zero, and skills start monitoring the related states to items. When a new state transition is detected, an specific event is emitted and the states are written in the short-term memory. The decision making module receives this event and states data are updated. Within robot lifetime, the action selection loop is executed in order to determine the next skill to be activated. At each iteration, the dominant motivation is computed as the maximum motivation whose value (internal needs plus external stimulus) is over its activation level. This parameter has been fixed to 10 for every motivation. Using the dominant motivation and the current states related to objects, the next action will be chosen.

This approach has already been implemented on virtual agents [18], [20], [19]. During these simulations and using reinforcement learning, Q-learning [32], the agent learnt the right q-values for maximizing its wellbeing. Currently, these ideas are being implemented in the social robot Maggie. At this work, we propose a set of values representing the best possible actions at each world configuration (the dominant motivation plus the state related to each object). The tuples formed by the dominant motivation, the object, the state related to the object, and the feasible actions will decide the selected action.

In some cases, the states and the actions are impossible. For example, for *playing with* people Maggie has to be *in contact* with a person. It does not make sense if *play with* action is activated when the robot is *alone*. At this point, values for these combinations are minimal and they will never be selected for execution.

During our first trials, after all values were fixed, the robot was programmed in such way that it always selected the best actions, it is those actions with the highest associated values. This leads to monotonous behaviours and the robot actions become very predictable. In order to allow *risky* behaviours, we have to

face the dilemma of exploration vs. exploitation, several times refereed in the field of reinforcement learning [29]. Level of exploration represents the probabilities of executing actions different than those with the highest values. Using Boltzmann distribution, probabilities for selecting an action in a state is given by (2).

$$P_s(a) = \frac{e^{\frac{V(s,a)}{T}}}{\sum_{b \in A} e^{\frac{V(s,b)}{T}}} \quad (2)$$

where $V(s, a)$ is the given value for action a in state s and A represents all possible actions in state s ; T is the *temperature* and it weights exploration and exploitation. High T gives the same likelihood of selection to all possible actions and the next action will be almost randomly selected; low T enforces actions with high values. As it is presented in [17], T value will be set according to equation 3.

$$T = \delta * \bar{V} \quad (3)$$

where \bar{V} is the mean value of all possible values. In experiments, δ was set to 1.

5 Conclusions

In this paper we present a decision making system based on motivations where no predefined goals are provided in advance.

The robot's aim is to survive satisfying its needs. In order to achieve it, robot's actions are based on the state of the robot which it is formed by its inner state (the dominant motivation) and the external state, it is the state into its "world". The "world" is sensed by sensory skills and actions are accomplished by skills as well. Both are running in the AD architecture.

The motivations, the drives and other values have been set having in mind that Maggie is a social robot intended for human robot interaction. This values will define its personality. The experimental tests carried out show that the robot is able to select the most appropriate behaviour autonomously, as a function of its state (internal and external). In the future, this selection will be learnt by the robot through its interaction with the environment. This learning process will take into account the emotions as a reinforcement function (happiness, sadness), implemented as another motivation for the robot.

Trials running our motivational system have proven a great *initiative*, Maggie is proactive executing actions even without human's request. However, since a robot's behaviour is not easy to predict, human-robot interaction will be more interesting for users because robot can take the initiative.

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On Internal Knowledge Representation for Programming Mobile Robots by Demonstration

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Abstract. Intuitive learning of new behaviours is one of the important aspects of social robotics. Among various robot learning approaches, recently *Programming by Demonstration (PbD)* has gained significant recognition with a lot of potential. Internal representation of the knowledge is a key design choice in the learning process. Using machine learning techniques such as ANNs, HMMs and NARMAX models, simple skills can be encoded from raw sensory data. However, the abstract symbolic representations have demonstrated greater potential for learning complicated tasks but with less details and require a piece of prior knowledge as well. For a particular application, appropriate choice of the symbols is a key design issue. This paper discusses the choice of the symbols to build a PbD process for typical indoor navigation. The learning results are presented for a few tasks to demonstrate the potential of the proposed approach.

1 Introduction

Apart from autonomy and interaction with humans, intuitive learning of new behaviours is also important for a good social robot. A social robot must be instructible by humans without specific skills and knowledge such as robot programming. A social robot is expected to be working in hybrid environments with humans where its role and/or the environment might be changing with time. It is infeasible for robot developers to foresee and preprogram a robot to adopt all possibilities it may come across. So, it would be quite interesting if a robot could be instructed by its human colleagues to adopt new scenarios, however they are not expected to have sufficient skills and technical knowledge to program the robot. In the past couple of decades, the focus of many researchers has been development of intelligent, interactive and easy to use robot teaching techniques such as PbD [5, 10], graphical programming [11], verbal communication [18], instructing through gestures [7], and/or a combination of these [11]. Recently, PbD has emerged with huge potential for end-user robot programming and gained considerable recognition [5, 10]. Compared to other end-user programming techniques, the main advantage of PbD is that the robot requires relatively less prior knowledge.

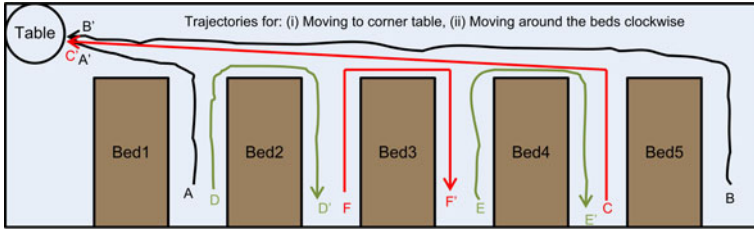


Fig. 1. Different trajectories for: i) the task of moving to the corner table (demonstrations: AA', BB', from the task model: CC'), ii) the task of moving around the bed clockwise (demonstrations: DD', EE', from the task model: FF')

This paper considers a generic problem of programming mobile robots for navigation in indoor structured environments such as labs, hospitals, elderly people homes and restaurants. One particular application of this research could be the joint health-care robot project of The University of Auckland and ETRI Korea [8]. The robot is expected to perform typical navigational activities such as required to deliver or collect objects, data and/or instructions by following the navigational plan of the user's choice. The challenge here is to deal with a huge variety of possible plans of the workspace and the changes in the workspace such as rearrangement of tables/beds and removal of temporary partitions. Each scenario requires a different program for the robot. The PbD abilities of the robot will allow the users to teach the robot for different environments. The paper focuses on the tasks which require/produce spatially different trajectories depending upon the initial state of the robot. The objective is to build the generalized task model from a few demonstrations to execute the task autonomously from different initial positions. For example, Fig. 1 shows the trajectories AA' and BB' for the demonstration of a task of moving to a corner table, and the trajectories DD' and EE' for the demonstrations of a task of moving around the bed clockwise. The PbD process is required to generate the generalized tasks models to move the robot on the trajectories CC' and FF' to execute the above tasks respectively starting from the positions not considered in the demonstrations. This paper focuses on the key design choice of internal task representation for PbD application in the area described above. The remainder of the paper is organized as follows. Sec. 2 summarizes the related work and highlights the issues to be addresses. Sec. 3 gives an overview of the proposed novel approach to address the issues and discusses the choice of the symbols for the task modeling. Sec. 4 presents the representations of a few example tasks.

2 Related Work

The design of the PbD learning process addresses two main questions: *what to learn?* and *how to learn?* [9, 10]. Generic solutions have not been found so far, however several different approaches have been proposed for different applications [5, 10]. Internal task representation is a key design choice in the

learning process which addresses the issue of *what to learn*. The other steps of the learning phase, such as segmentation, abstraction and generalization, address the issue of *how to learn* i.e. how to build a task representation from traces of sensory data collected during the demonstrations. This paper addresses the first issue for PbD of robots in general and for the healthcare robot in particular.

“The user’s intentions behind the demonstrations” could be a generic answer to *what to learn*, it depends upon the target application. For example, in some cases users could be interested in fine details such as the profile of position, velocity and/or torque, however in other cases they might be interested in the overall effect or the final state alone [5, 10]. The diversity of the user’s intentions and learning objectives led to several task representations in the past [10].

Machine learning techniques, such as artificial neural networks (ANNs) [6, 14], hidden Markov models (HMMs) [1], NARMAX models [15] and echo state networks [12], have been used for generalized encoding of simple skills. Hand trajectory learning from multiple demonstrations is addressed in [4] using clustering and stochastic methods. The robustness of hidden Markov models has been exploited for trajectory learning in several cases [1, 10]. ANNs [6] and NARMAX models [15] have been used to learn direct relationships between the sensory data and the corresponding actuation for tasks such as wall following. The advantages of machine learning approaches are that they use raw sensory data, they do not require prior knowledge for inferencing, and they can encode different types of motion trajectories, signals and gestures. However, they require many examples and cannot be extended for complicated high level tasks where the variation in sensory data is large over multiple demonstrations [10].

For high level tasks, **symbolic representations** have demonstrated potential. In the symbolic representation approach, the demonstrations are segmented according to predefined rules where each segment generally corresponds to a predefined action *primitive* [7, 13, 16, 17, 19]. The demonstrations are transformed into sequences of primitives. From multiple demonstrations, the task is encoded as the generalized arrangement of the primitives and may take several forms. HMMs has been used in [17] to learn a generalized sequence of primitives. Hierarchical arrangements have been used in [13, 19]. The flexibility in sequential arrangement has been exploited using task precedence graphs (TPGs) in [16]. In some cases, the task is a static arrangement of the primitives [17, 19]. However in other cases, *pre/post conditions* are used as another type of symbol, which help dynamic selection of the primitives at runtime [7, 11, 13]. For high level tasks, sometimes flow charts are used [7, 11, 18] with conditional branches, loops and interrupts [18], however they require human interaction and feedback. The advantage of the symbolic representations is that they can be used to build complicated tasks using simple building blocks, however fine details are lost in the process of abstraction. Moreover, they require some prior knowledge in the form of predefined symbols and segmentation rules.

Symbolic task representations use two types of symbol: i) *Primitive actions*, and ii) *Predicates* [7] or *pre/post conditions* [11, 13, 18]. The primitives generally abstract basic atomic actions such as *move forward/backward*, *turn right/left* [7],

close/open gripper and *move arm* [11]; whereas predicates abstract the conditions or criteria to select or terminate a primitive action during execution.

2.1 Issues

For the class of tasks described in Sec. 1, which require different trajectories to be followed to achieve the task goals, this paper considers the following issues:

- Each demonstration produces a different sequence of primitives due to human variations and/or depending upon the initial state. For a potentially infinite number of scenarios, the generalization from multiple demonstrations using statistical approaches such as HMMs [17] is inefficient as it requires a huge number of demonstrations;
- Alternatively, in some cases the generalization requires more information from the demonstrator, perhaps via a graphical interface [7, 11] or in the form of verbal comments [18]. However it could be annoying for users to provide this information while demonstrating complicated tasks and therefore may require some user training, experience and/or the system specific knowledge.

3 The Proposed Approach

The design of higher level symbols could be a potential solution to the first problem. Generally, a higher level symbol can encode the effects and features of several low level symbols resulting in a shorter symbolic description of each demonstration. Thus higher level symbols can simplify the problem of learning the generalized arrangement of the symbols, particularly when several different arrangements of the low level symbols (e.g. primitives) produce the same effect (e.g. the same trajectory).

The choice of an appropriate set of symbols is a key decision. Generally, the PbD processes are developed on a set of symbols of the developer's choice, and the choice of the symbols has not followed any formal or consistent rules. However, a few properties are typically considered qualitatively such as *simplicity of the task models*, *modeling potential for complicated tasks*, *number of featured captured*, *reusability of the symbols* and *the amount of prior knowledge*. The higher level symbols simplifies the overall task model and demonstrate improved *learning potential* for complicated tasks [10]. However such systems may lose several features, such as velocity and acceleration profiles, of the demonstrations and generally require more *prior knowledge* such as predefined abstraction rules to identify the symbols from the demonstrations. So, as long as all the important task features could be captured, higher level but generic symbols must be preferred to improve the learning potential. For the application under consideration, the sequence of moves is not as important as the resulting trajectory. So instead of segmenting into a sequence of basic atomic moves, the trajectory could be better modelled as a piecewise linear curve. Each line segment will represent the effect of several basic moves, without losing any important information but human imperfections i.e. small deviations from the linear trajectory as discussed in [3]. So we propose

a novel PbD process based on piecewise linear modeling of the demonstrated trajectories. The proposed approach consists of the following steps:

1. The robot is teleoperated to teach the navigational plan from various initial states to the target;
2. The demonstrated trajectories are segmented and modeled as piecewise linear curves;
3. The corresponding segments from multiple demonstrations are identified and grouped together;
4. The user's intentions represented by the consistent features of the groups of the corresponding segments are abstracted and generalized as the symbols called the *Elementary Targets* (ETs);
5. The user's intentions represented by the consistent conditions (i.e. the state represented by the sensory data) at the instant of the transition from one trajectory segment to another are abstracted and generalized as the symbols called the *Execution Control Rules* (ECRs);
6. A generalized arrangement of the ETs and ECRs (called the task model) is learnt from multiple demonstrations;
7. Using the task model and the prior knowledge, the robot performs the task autonomously.

The trajectory segmentation (step 2) has been discussed in [3]. [2] discusses the trajectory generation as a part of the prior knowledge (step 7). Here the choice of the ETs and the ECRs is discussed (step 4 and 5). The correspondence problem (step 3) has not been addressed yet for complicated cases where the trajectory segments at the same index in different sequences of the trajectory segments (i.e. multiple demonstrations) might not be corresponding segments. Here the proposed symbols are used to encode the sequential tasks i.e. the linear segments at the same index in different demonstrations correspond to each other.

3.1 Elementary Targets

To simplify the task description and generalizations, the primitive moves have been replaced with higher level symbols, ETs. So ETs must capture those features of the demonstrations that help produce actuation commands for what the robot primitives do. In our case, ETs are generalized abstract representations of the corresponding trajectory segments, so different features of the linear trajectory segments are considered when designing different types of ETs.

The linear segments and the corners could be modelled as *move forward* and *turn* behaviours respectively. However various versions of the *move forward* and the *turn* are required to generalize the features of corresponding segments and corners such as the line segments of the same length, the line segments ending at the same position, the corners of the same angle, the corners of different angles but resulting in the same orientation of the robot, and the corners showing the turning towards a fixed position target. The proposed approach uses three types of ETs — *the absolute position target*, *the absolute direction target* and *the relative direction target* — to capture all the features mentioned above.

The absolute position target (x, y) represents the user's intention of moving the robot to a fixed absolute position and is identified from multiple demonstrations when the corresponding segments of the trajectories end at approximately the same position $(x \pm \varepsilon, y \pm \varepsilon)$ (see Fig. 2).

The absolute direction target (θ, l) represents the user's intention of moving the robot towards an absolute direction and is identified from multiple demonstrations when the corresponding trajectory segments run in parallel in approximately same direction $(\theta \pm \delta\theta)$ (see Fig. 2).

The relative direction target (ϕ, l) represents the user's intention of moving the robot towards a relative direction with respect to previous direction of motion and is identified from multiple demonstration when the corresponding trajectory segments make approximately the same angle with their corresponding previous segments $(\phi \pm \delta\phi)$ (see Fig. 2).

If the lengths l of the corresponding trajectory segments are found to be approximately the same $(l \pm \delta l)$, it is used as second parameter of the *absolute* or *relative position targets*. A *relative position target* is not required as it is same as moving a fixed distance in a desired relative direction.

Hence, the ETs capture the generalized features of the demonstrations which help produce an appropriate trajectory for the playback of the learned task. The ETs are similar to the primitives as both generate traces of the controller commands, however the ETs are better since:

1. The ETs abstract generalized features of corresponding segments of multiple demonstrations whereas the primitives encode individual demonstrations, hence the ETs resolve the task generalization problem to some extent;
2. The ETs use higher level segmentation, i.e. linear trajectory segments, to produce shorter descriptions of the demonstrations and hence again simplify the problem of generalization;
3. The ETs use piecewise linear models of the trajectories and hence reduce inconsistencies caused by human imperfections [3];
4. The predefined control functions corresponding to the ETs produce smooth trajectories for the line segments without irregular variations in the velocity and acceleration [2] instead of switching between different primitives.

3.2 Execution Control Rules (ECRs)

During the playback, the task model is expected to guide the robot on a generalized trajectory i.e. a sequence of linear segments. So the system selects the

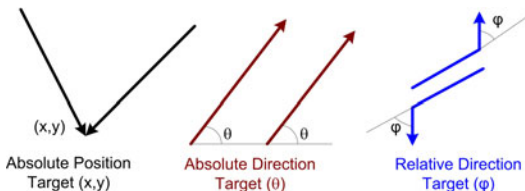


Fig. 2. The proposed ETs

ETs one by one for each desired line segment. Sometimes, the end point of the linear segment is known as the parameters of corresponding ET. For example, the *absolute position target* uses the end point (x, y) as its parameters, and the parameters (θ, l) of the *absolute and relative direction target* can be used to calculate the end point. However, if the length parameter l is not known (i.e. found inconsistent in the demonstrations), some other consistent features of the demonstrations, such as relative position of the robot with respect to other objects, need to be investigated to switch from one ET to another. Such features are abstracted as another type of symbol, ECRs. Here two ECRs are introduced based on the range data and the robot's position in a certain region.

The range based ECR ($FR \pm \delta, RR \pm \delta, LR \pm \delta$) describes the transition criterion based on the relative position of the robot compared to other objects in the environment. Any range sensor, such as sonars or a laser range sensor, can provide this information. We are using a tuple of sonar values $(FR, RR, LR) \equiv (FrontRange, RightsideRange, LeftsideRange)$ to describe the range state of the robot. If all the trajectory segments corresponding to an ET end at the similar value of one or more attributes of the range state $(FR \pm \delta, RR \pm \delta, LR \pm \delta)$, the system infers that the user is interested in moving the robot up to that particular state. In Fig. 3, the trajectory segments BC and $B'C'$ run in parallel but have different lengths and so are modelled as an *absolute direction target* without the length parameter. However the system discovers that the line segments end at almost the same state of sonar values (i.e. the robot heading towards a wall and there is no object at right and left), so the range based ECR can be used here as the termination criterion for the corresponding ET.

The region based ECR describes the transition criterion for an ET based on a specific region of the workspace. If the end position (x, y) , the length l and range based ECRs are not valid (none of them are consistent over all the demonstrations), the system infers that the user is interested to move the robot to a region containing the end points of all the trajectory corresponding segments. In Fig. 3, the trajectory segments AB and $A'B'$ end at different positions, have inconsistent sonar states and have different lengths, but the robot is required to turn right and move to the corridor. In this case, it is quite hard to know when the robot has reached in front of the door. This condition is difficult to generalize. In such situations, we use ANNs to learn the region based ECRs. 100 points (x_i, y_i) are randomly selected as *false* cases (the states indicating the robot is not in front of the door) on the line segments and 100 linear combinations of endpoints of the line segments (x_j, y_j) are taken as *true* cases (the states indicating the robot is in front of the door). Here (x_{ei}, y_{ei}) is the end point of the i^{th} line segment corresponding to the ET, $(x_j, y_j) = w_{j1} \times (x_{e1}, y_{e1}) + w_{j2} \times (x_{e2}, y_{e2}) + \dots + w_{jn} \times (x_{en}, y_{en})$; and w_{ji} is a randomly selected weight such that $0 \leq w_{ji} \leq 1$ and $\sum_{i=1}^n w_{ji} = 1$. The back propagation ANN trained for these 200 points generally helps to model the transition conditions based on the region. During playback, the trained ANN will return *true* when the robot will approach a region in front of the door (left side of the dotted line in Fig. 3).

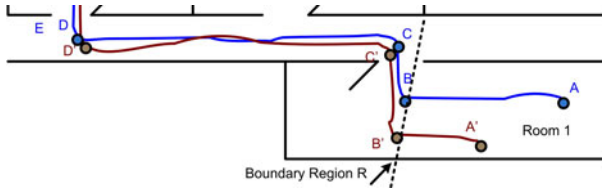


Fig. 3. A couple of demonstrated trajectories to move the robot from room1 to corridor

More ECRs could be defined for other types of inputs and feedbacks when helpful in the decision-making such as a voice command to start or stop a particular action.

4 Representation of a Few Example Tasks

The piecewise linear modeling of the trajectories and abstraction result in a sequence of the ETs and the ECRs. Fig. 4 presents the trajectories for the demonstrations and the playback of two example tasks. To demonstrate **the task of moving from room 1 to room 2**, the robot is moved from two different positions (room 1). The demonstrated trajectories are shown as solid lines. The segments shown in same color on both trajectories correspond to each other. The abstraction results in the task representation listed in Table 1 (left column). Fig. 4 shows the first segment of both demonstrated trajectories (blue) directed towards the same direction approximately (average: 1.6 degrees) and hence modelled as an *absolute direction target (1.6)* (see Table. 1). The line segments end at different positions, have different lengths and have different range states, so the transition criterion is modelled by *network 1* as a region based ECR. The remaining task is modeled in the same way. The negative parameter of the range based ECRs represent inconsistent range states. During the playback, the PbD system uses the learned symbolic representation to execute the task from two different positions. The playback trajectories are shown as red tracks in Fig. 4. The representation and the trajectories for another example task of moving around a bed in room 3 are shown in Table 1 and Fig. 4.

Table 1. The representation of the example tasks

Moving from room 1 to room 2	Moving around the bed in room 3
Absolute direction target(1.6)	Absolute direction target(2.3)
Region based ECR (network1)	Range based ECR(-1,-1,3)
Relative direction target(88.3)	Relative direction target(90.1,2,3)
Range based ECR(0.75,-1,-1)	Relative direction target(88.6,3,4)
Relative direction target(-89.9,1,76)	
Absolute position target(-1.0,3,2)	
Absolute position target(-7.8,3,05)	

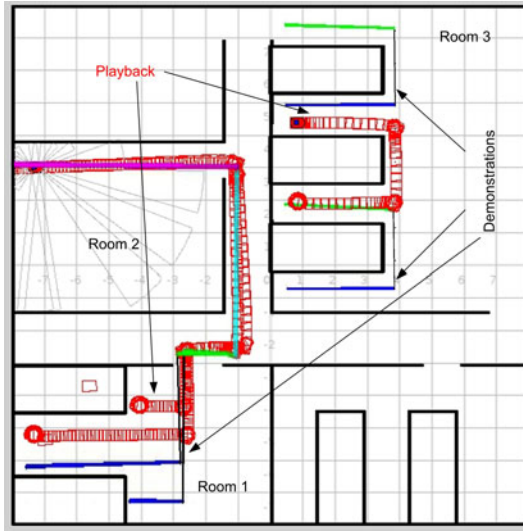


Fig. 4. The robot trajectories for the demonstrations and the playback of the tasks of: i) moving from room 1 to room 2, ii) moving around the bed anti-clockwise in room 3

The playback shows the successful learning of both tasks from a couple of demonstrations for each. The demonstrations start at different positions and orientation of the robot so require different moves to reach the target. Moreover there could be inconsistencies coming from human imperfections that can not be filtered by spatial clustering for the trajectories running between different end points. So a generalized arrangement of the primitives is quite hard to learn from just a couple of demonstrations. However the proposed approach reproduces the desired behaviour.

5 Conclusions

The paper presents a novel approach for PbD of the navigational tasks which uses higher level symbols, the ETs and the ECRs, than the primitives used in the previous approaches. Unlike the primitives, the ETs are abstracted from multiple demonstration and encode the consistent features of the demonstrations and hence improve the learning potential of the PbD system by resolving the generalization problem to some extent. Currently, sequential tasks have been considered. The demonstrations capturing different aspects of the tasks, such as conditional actions, will produce different sequences of the linear segments (ie non sequential tasks). The correspondence and generalization problems for such tasks need to be investigated in future.

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A Software Framework for Multi Player Robot Games

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Abstract. Robot games have been proposed as a way to motivate people to do physical exercises while playing. Although this area is very new, both commercial and scientific robot games have been developed mainly based on interaction with a single user and a robot. The goal of this paper is to describe a generic software framework which can be used to create games where multiple players can play against a mobile robot. The paper shows how an adaptive AI system (D2) developed for real-time strategy (RTS) computer games can be successfully applied in a robotics context using the robotics control framework Player/Stage. D2 is based on Case-Based Planning which learns from demonstration. Using the proposed framework, the paper shows how a robot learns a strategy for an implementation of a simple game.

Keywords: Human Robot Interaction, Games, Artificial Intelligence.

1 Introduction

Based on the demographic development in most western countries, it has been predicted that the number of people with mental and/or physical disabilities will increase while the amount of people to take care of them will decrease [26], [2]. Digital games hold a significant promise for enhancing the lives of seniors, potentially improving their mental and physical wellbeing, enhancing their social connectedness, and generally offering an enjoyable way of spending time [14]. It has been shown that mental and physical health can be improved through a small amount of physical exercises [24], [10], and e.g. Nintendo Wii has been suggested as a means to increase physical activity among elderly [4], [18].

In this paper we introduce a software framework for constructing robot games which motivates people to move physically when playing. The framework provides generic functionality which can be selectively overridden or specialized by user code providing specific functionality for creating a number of games using mobile robots. Many known games are derived from a pursuit-evasion scenario e.g. the child games robbers and cops and the game of tag [21], and in this paper we describe a concrete implementation of a game where multiple players compete against the robot.

The vision of robots participating in our day-to-day lives is the focus in the research field of Human Robot Interaction (HRI) [7]. The vision is supported by progress in the development of new sensor technology and computing, which open the door to a new generation of mobile robotic devices that see, hear, touch, manipulate, and interact with humans [11]. The development is reflected in the fact that computer games are gradually moving from the pure virtual domain into the physical world with the introduction of products like Nintendo Wii, Microsoft Kinect, Sony's EyeToy, etc. There are several examples of how games are constituted using a physical robot, e.g. QRIO's routine of tracking and kicking a ball, and in [3] where the robot Leonardo is used to play an imitation game. In [23] we have described a game where a mobile robot can play a simple ball game with a human. Some commercial gaming robots exist, e.g. Tri-Bot from WowWee which is able to play three simple maze-based games with the user.

Although there has been a great advance in computer games in computer graphics, animation and audio, most of the games contain very basic artificial intelligence (AI) [17]. To deal with increasing complexity there has, however, been a push for the development of new AI algorithms, many of which shares requirements with those of robots operating in open-ended environments.

In this paper we will shortly summarize the background for making robot based games and outline some of the requirements. We introduce D2 which is an AI system based on case based planning. D2 is originally developed for real time strategy computer games and we show how it can be used in a robotics scenario also. This is done by implementing a game interlinking D2 with the robot control software Player/Stage.

2 Background

Motivating users to move physically by playing a game is related to persuasive technology which is defined as technology designed to change attitudes or behaviors of the users through persuasion and social influence, but not through coercion [8] and [9]. Robots offer advantages not found in on-screen agents or technology embedded in the environment, such as an increased sense of social presence in an interaction and the capacity for touch and physical interaction [15]. In [12] and [13] the concept of enjoyment as a possible factor influencing acceptance of robotic technology was investigated using the iCat Research Platform which is a robot research platform for studying human-robot interaction. The fact that sociable robots are more fun to play with was confirmed in [16]. Successful games are often characterized using the concept Flow, as proposed by Csikszentmihly [6] which is a mental state which can occur when there is an appropriate balance between challenge and skill. As the cognitive and physical capabilities of the users are expected to vary, the robot should adapt the difficulty of the game to the end user. The fact that intelligent agents working in real time domains need to adapt to changing circumstance has been recognized in computer game industry as well as in robotics. The ability to adapt is necessary in order for autonomous agents to improve their performance and avoid mistakes in a complex and dynamic environment.

As robot sensors gradually get more reliable and new types of sensors emerge, the robot's knowledge about the real world is getting more precise and informative. Computer games are on the other hand developing towards more complexity with an increasing high decision space, involving interactive users and real time performance.

This makes the AI requirements from these two distinct domains intersect and some of the common characteristics are:

- Real Time Nature: imposing constraints in terms of processing time that could be taken by AI approaches situated within these domains.
- Large Decision Spaces: most state of the art computer games have huge decision spaces [5], [1], and thus traditional search based AI techniques cannot be applied. The same applies for robots which should act in open ended environment relying on multiple sensors.
- Unanticipated Scenarios: it is not feasible to anticipate all possible situations and as result, it is hard to design behaviors that can handle all the possible situations and respond appropriately to all possible actions.
- Human in the loop: Games involve one or more interactive user(s) that can change the state instantaneously. Even small delays in AI decisions can be unacceptable.

A popular approach to deal with non-determinism is to use planners based on reinforcement learning, e.g. by modeling the problem as a Markov decision process and focus on learning a policy. These techniques, however, often require a large number of iterations to converge. In complex domains, they are intractable and generalize poorly [17]. While reinforcement learning approaches are good for low level control, symbolic approaches like Case Based Planning are good for high level strategic decisions which is the focus of D2 which we present here.

2.1 The D2 System

D2 [19] is a real-time case-based planning system designed to play Real-Time Strategy games (RTS). D2 implements the *on-line case-based planning cycle* (OLCBP) as introduced in [20]. The OLCBP cycle attempts to provide a high-level planning systems that operate on-line, i.e. that interleave planning and execution in real-time domains. The OLCBP cycle extends the traditional CBR cycle by adding two additional processes, namely *plan expansion* and *plan execution*. The main focus of D2 is to explore learning from human demonstrations, and the use of adversarial planning techniques. The most important characteristics of D2 are:

- It acquires cases by analyzing human demonstrations.
- It interleaves planning and execution.
- It uses an efficient transformational plan adaptation algorithm for allowing real-time plan adaptation.
- In case a simulator is available, D2 can make use of it to perform adversarial case-based planning.

For D2 to learn how to perform a given task, an expert has to provide demonstrations of such task. D2 can typically learn from a few demonstrations (1 or 2), but depending on the variability of the domain or the complexity of the task, many more traces might be needed.

D2 has been used as an AI engine for several computer strategy games like Wargus (open source clone of Warcraft II), BattleCity, S2, Towers and Vanquish (clone of Risk), and is currently being applied to Starcraft. A previous version of D2 (Darmok) was applied to a game scenario where two virtual characters played a game of tag [17].

3 A Robot Game

In [23] we presented a game based on a simplified pursuit and evasion scenario. The human player should try to hand over a ball to the robot, while the robot should try to avoid receiving the ball. The robotic platform which formed the basis of these experiments, is shown in Figure 1. The robot platform from FESTO is equipped with a head having 126 red diodes (see Figure 1) which enables it to express different emotions. The robot is 1 meter high, and has mounted an URG-04LX line scan laser placed 35cm above ground level, scanning 220 degrees in front of the robot. In [23], an on/off switch was placed to find out when the robot had the ball.

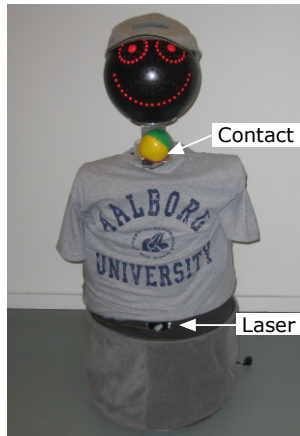


Fig. 1. The modified FESTO Robotino robotic platform

Based on the same robotic platform on which we have added a standard web camera, we suggest a similar simple pursuit and evasion game which allow multiple users to play with the robot. The game consists of a number of squares marked on the floor, a mobile robot and a number of human players. The winner of the game is the participant who has visited all squares first. During a game, the robot can tag a person which makes the person do a detour on the game board. The implementation of the game has been done using the following components (see also Figure 2):

1. A Robotics Environment which takes care of control of simulation and control of the robot (Player/Stage)
2. An AI Engine which learns and executes the robot's overall gaming decisions (D2).
3. A Game Application, which defines the frame and the purpose of the game and works as the interlink between the two former elements. Here we have chosen an implementation of a variation of the Game of Tag, but many other games could be interesting.



Fig. 2. Illustration of the three components of the framework; a robot controller (Player/Stage), an interlinking game application (Tag Game) and an AI engine (D2)

3.1 The AI Engine

In order to implement D2 as the AI engine for a game, the following elements should be defined in a XML file following a specific D2 syntax: Entities, Sensors, Actions, Preconditions, Postconditions and Goals.

An Entity is a definition of the basic units of the game. In this case there are four: the human players, the robot, the squares marked on the floor and a wall entity. The latter is used to mark the barriers of the game area and obstacles in the game area. Each entity specification holds the name of the entity and a list of which actions are available to the entity.

The Sensor definition describe the robot's sensor input in any level of abstraction. In this case, this is the position values of the entities. Securing that the position of the player and the robot is actually correct is not in the scope D2 but is handled by Player/Stage and will be described later.

The Action definition is a list of all possible actions the entities can do. The low level implementation of these robot actions is not in the scope of D2 either but is handled by Player/Stage. D2 has the function of learning to select the right actions during a game in order for the robot to win the specified goals.

The Goal definition is specification of how to win the game, which in this case is when the robot has visited all squares. With all elements above properly defined, the D2 framework can auto generate a number classes which forms the basis of the game in the Game Controller. This can be interlinked to a robot controller and simulation environment like e.g. Player/Stage.

3.2 Control and Simulation Environment

Player/Stage handles a simulation environment and the low level robot control including position detection, path planning and collision avoidance. It also holds a pre-defined map of the environment which is read from a file.

The position of the robot is done using the standard Player/Stage amcl driver which implements the Adaptive Monte-Carlo Localization algorithm described by Dieter Fox. The amcl driver maintains a probability distribution over the set of all possible robot poses, and updates this distribution using data from odometry, laser range-finders and the pre-defined map of the environment. The detection of the players' position is done by the robot using the mounted laser scanner using a leg detection algorithm [25] and [22].

Collision avoidance is done automatically in Player/Stage by implementing the Vector Field Histogram Plus local navigation method by Ulrich and Borenstein. VFH+

provides real-time obstacle avoidance and path following capabilities for mobile robots and in order to obtain global navigation, the wavefront driver has been layered on top of that. When simulating the game, the human players have been modeled using the obstacle avoidance and path planning functionality offered in Player/Stage. Each player has been modeled having a different color and a standard Player/Stage blob-detection algorithm for web camera input is used to distinct the players from each other.

3.3 The Game Controller

The game controller is basically the game definition and the interlink between the AI Engine and the Simulation Environment. It constructs the game scenario by passing selected actions from D2 to the robot implementation and sensor data from the robot the other way. The game strategy of D2 is created using initial demonstrations, allowing a game instructor to control how the robot should act. In this implementation, demonstration is done by facilitating a GUI where the instructor can choose between the different robot actions. During this process, the Game Controller generates traces which are used by D2 to learn a strategy about the behavior of the robot and the players. When a strategy has been learned, the game controller can let D2 control the behavior of the robot without human interference. In a simulated environment, the Game Controller to some extent also specifies how the persons play the game, i.e. it controls to which position the persons should move. In the current implementation, the game controller can handle any number of squares and players but only one robot.

4 Experiments

We consider a simplified game setup to illustrate and validate the basic functionality of the proposed framework. In each game, the players, the robot and the squares are placed at random positions. The participant who first visits all squares, wins the game. While the simulated human players use a nearest neighbor algorithm to select where to move, the robot can choose between the following actions:

- Move To Square. Make the robot move to a specified square.
- Tag Player. Make the robot follow a specific player. If the distance between the robot and the player is under a specific threshold, the player is tagged and he/she should do a detour by moving to a specific position on the game board.
- Rotate left/right. Rotate the robot left or right from its point of view.
- Move forward or backwards.

In order for D2 to learn a strategy, two games have been completed using a human demonstrator. This is sufficient for D2 to learn a strategy, which now can be used to control the robot. Five different variations of the game have been tried out.

1. The simulated players play against each other without the robot. Each person is moving with a max speed of 0.5 m/s.
2. The speed of one player is set to move slower, having a max speed of 0.1 m/s.

3. The robot is introduced in the game, having a max speed of 2 m/s.
4. As before, but the game field now consists of 10 squares.
5. As 3, but now a goal has been added which states that all players should have visited at least 3 squares before the game ends. In this experiment, the robot has been retrained using a human demonstrator.

Each game has been repeated a total of 20 times for each experiment, and the number of won games by each player can be seen in table 1. The maximum, minimum and mean number of game rounds can be seen in table 2. Figure 3 shows a screenshot from a simulated instance of the implemented robot after a few seconds of playing time. On the figure, it can be seen that each player including the robot has moved on to a square and is looking for a new square to visit.

Table 1. Number of won games by each player in 5 experiments with 20 games in each

Games won	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5
Person 1	10	20	4	0	13
Person 2	10	0	0	0	2
Robot	0	0	14	13	2
N/A	0	0	2	7	3

Table 2. The minimum, maximum and mean number of game rounds in 5 experiments with 20 games in each

Game rounds	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5
Min	105	101	59	150	221
Max	278	207	139	238	707
Mean	169	189	103	181	435

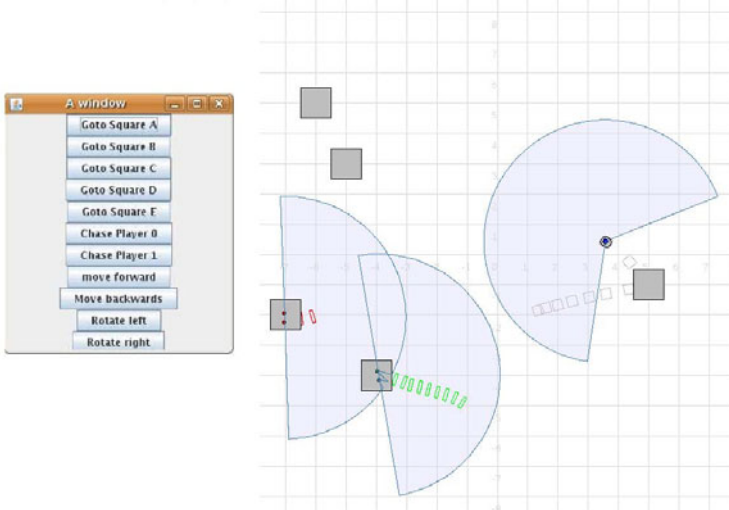


Fig. 3. The figure shows a screenshot of the implemented robot based game. Each player is moving from the initial position to a square marked on the floor. The window to the left is a GUI, which initially lets a human user demonstrate how the robot should behave in order for D2 to create a control strategy.

5 Discussion

In the first column in table 1, it can be seen that the two participating persons win an equal amount of times. This is as expected, as both persons use the nearest neighbor algorithm and move with the same speed. In experiment 2, person 1 wins all the games which is also as expected as this player is capable of moving faster than its competitor. In experiment 3 the robot is introduced and it wins 14 games. This shows that the robot has learned a valid strategy, and since it moves faster it is most likely to win. It is surprising that person 1 actually wins 4 of the games. This is considered to be due to the fact that the robot not has learned an optimal strategy, and to some degree due to a fortunate location of the squares in played games. Two of the games does not end with a winner, because the players are stuck in a deadlock where each one is blocking the way of the others. In experiment 4, the number of squares is increased. Now the robot wins 13 games, the persons win none, but 7 games ends without a winner because simulation has been aborted after a 1000 game rounds. In the last experiment, a goal has been added which states that all players should visit at least 3 squares. Although person 1 wins the majority of the games, person 2 actually manage to win 2 games although he/she is moving much slower than the other participants. Although the robot is capable of winning more often because of its higher speed, it only wins two of the games. This is due to the fact that a new goal has been added, and the robot now spends time on tagging person 1 to ensure that person 2 reaches at least 3 squares before the game finishes. Although more research is needed, this final experiment is included to illustrate that the robot can learn a strategy making all participants capable of playing although they have very different skills. Table 3 shows the maximum, minimum and mean number of game rounds for all experiments. It is worth noticing that the mean number of game rounds increases in experiment 5, because the robot now spends more time tagging the other players.

The presented gaming framework is still at a very early stage, and therefore results have been obtained through simulation only. This reduces the complexity of the game scenario, because getting precise data like e.g. the location of the robot and the players is not a simple problem in the real world. The actual behavior patterns of the human players are also simplified and should be elaborated through real world experiments. The results show that D2 can be used to learn a playing strategy for robot based games. It is important to notice that here the goal of D2 is not necessarily to make the robot play optimal, as this could have been archived with simpler means. The focus is to create a strategy for the robot which ensures a balance between skill and challenge for the participating players during the game. The contribution of this paper is to introduce a generic software framework applicable for multi player robot games. The framework is constructed by interlinking D2 with Player/Stage, each of which have been validated many times in other papers and therefore forms a good basis for further research.

6 Conclusion

In this paper we have outlined a generic software framework which can be used to implement robot based games where multiple human players can compete against a mobile

robot. The framework consist in a Case Based Planner (D2) which is interlinked with Player/Stage which serves as a robot control and simulation environment. We have implemented a variation of the Game of Tag for a mobile robot competing against multiple human players. Using the framework, we have showed that the robot can learn different game strategies based on a few demonstrations. A possible application for robot based games is to motivate elderly to do a higher amount of physical exercises and thereby strengthen their mental and physical capabilities.

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A Behavior Adaptation Method for an Elderly Companion Robot—Rui*

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Abstract. This paper describes the state-of-the-art of an elderly companion robot project, aimed towards the development of personal service robots for the elderly population. We propose a behavior adaptation method that reads interaction signals from the old people, and then adjust interaction output such as daily dialogues, news and whether broadcasting, motion speed and navigation-assist. The method uses detecting the user's speech command, touch-screen input, head position and body posture as subconscious signals that indicate a user's interaction preference. A study with the elderly companion robot that has six interaction behaviors has been conducted. The study result of 8 subjects preliminary suggests that the proposed mechanism enables adaptation to individual preferences.

Keywords: Behavior adaptation, human-robot interactions, elderly companion robot.

1 Introduction

The number of elderly in need of care is increasing dramatically. The dramatic increase of the elderly population along with the explosion of costs poses extreme challenges to the society. The current practices of providing care for the elderly population are already insufficient. Undoubtedly, the problem will multiply over the next decade. Thus, as a society we need to find alternative ways of providing care to the elderly and chronically ill population. Such ways will not only lower the costs, but also increase the comfort of living, and approach people with the level of dignity that our elderly deserve [1].

Robotic technology, at the same time, is going through major revolutions. Sparked by a dramatic increase of computation per dollar, and by substantial decreases in the costs of major sensor technologies such as CCD cameras and ultrasonic sensors, we are now closer than ever to the goal of intelligent service robots than can assist people in their daily living activities.

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Robots designed for the home are a growing industry from both a research and commercial perspective. Robot companions are expected to communicate with non-experts in a natural and intuitive way [2]. A companion robot will generally be acting in an unstructured environment, such as a private home or a rest home for old people, with people roaming around. Companion robots in the home should ideally be able to perform a wide array of tasks including educational functions, home security, diary duties, entertainment, message delivery services and so on. Currently, there are no robots that are able to perform a combination of these tasks efficiently, accurately and robustly. Since it is not desirable to rely on pervasive sensor technology distributed throughout the environment, the companion robot has to carry all sensing devices on board.

At the same time, there has been little research to date in terms of assisting elderly people with cognitive tasks, such as remembering medication schedules. However, human-robot interaction, autonomous systems and planning have seen major developments recently [3]. Human-robot interaction research is still relatively new in comparison to traditional service robotics where robots deliver hospital meals or provide security services, application domains that require relatively minimal human-robot interaction [4].

Partially Observable Markov Decision Processes (POMDP) is a method for calculating optimal control actions under uncertainty. They are useful for a wide range of real-world domains where joint planning and tracking is necessary, and have been successfully applied to problems of human-robot interaction. The POMDP model has the ability to handle problems of optimal control with hidden state in continuous and partially observable environments, but requires a known model to be solved. This is a limitation in practice as the exact model parameters are often difficult to specify exactly [3].

In this paper, we propose a behavior adaptation method based on hierarchical POMDP (H-POMDP). Using speech command, touch-screen input, head position and body posture from the user as the observation for the reward function, it simultaneously studies the behavioral parameters that maximize the reward, in order to fit the user's interaction preference. We use a reward function that consists of the user's info query and navigation-assist rate in human-robot interaction. In the following, we first introduce the hardware design of the companion robot --- *Rui*, and then explain the proposed behavior adaptation method. After that, we set up the pilot study and setting, then give the experimental results. Finally, we present the conclusions and future work.

2 Related Work

ROBITA[5] has a humanoid torso with cameras and microphones embedded in the robot's "head". Both use a combination of visual face recognition and sound source localization for the detection of a potential communication partner.

SIG[6] is directed towards the person currently speaking that is either approaching the robot or standing close to it. In addition to the detection of talking people, ROBITA is able to determine the addressee of spoken utterances.

Care-O-bot II [7] is a multi-functional robot assistant for housekeeping and home care, designed to be used by elderly people. It receives input from the user via speech

and touch screen. Although the system also produces speech output, it can not carry out natural dialogs with the user.

Lino [8] serves as user interface to intelligent homes. It perceives persons by processing visual and auditory information. Since the robot operates in an intelligent environment it makes use of external information sources.

The humanoid service robot HERMES [9] can be instructed for fetch-and-carry tasks, and it was also adopted as museum tour guide. It integrates visual, tactile, and auditory data to carry out dialogs in a natural and intuitive way, but can only interact with single persons.

Jijo-2 [10] is intended to perform tasks in an office environment, such as guiding visitors or delivering messages. It uses data coming from a microphone array and a pan-tilt camera to perceive persons.

Several behavior adaptation systems for human-robot interactions have been proposed. In [11], incremental learning of decision-making rules for a mobile robot is proposed, which learns the user's preferences through the commands. In [12], a virtual agent that learns according to the conversations of users is proposed based on reinforcement learning. However, the agent needs the user to consciously response to the robot, it is difficult for the people communicating with the robot smoothly. In [13], a behavior adaptation system based on policy gradient reinforcement learning (PGRL) is proposed, using human's movement distance and gazing period as input for the reward function.

3 Hardware Design

The current prototype robot, called Rui is shown in Figure 1. Rui is built on top of a Nomad Scout differential drive mobile base, equipped with 8 ultrasonic sensors and



Fig. 1. Side view of the robot---*Rui*. The robot is equipped with a touch-sensitive display, an array of 8 sonar sensor and 8 infrared sensors, and a laser range finder.

8 infrared sensors. The robot is equipped with a URG-04lx-ug01 laser range finder, capable of measuring distances at an angular resolution of one degree and a spatial resolution of 5 cm, within a planar perceptual field that covers a 180 degree range. Rui is also equipped with two on-board PCs, connected to the Internet via a 2Mbit/sec wireless Ethernet link. A bright, touch-sensitive color display is mounted conveniently at approximate eye height for sitting people.

Rui is equipped with a colour CCD camera with an approximate aperture angle of 100 degrees. The camera is connected to a frame grabber and JPEG encoder for image processing and high-bandwidth communication. *Rui* is also equipped with a speaker system and a microphone array, necessary for recording and synthesizing speech. *Rui's* battery lifetime is approximately 60 minutes. The robot currently lacks a mechanism for connecting itself to a battery charger, making it necessary that a human assists the robot in operation.

4 Behavior Adaptation Method

POMDP provides a mathematic model that permit to characterize the type of uncertain systems. A POMDP model represents the dynamics of the environment, such as the probabilistic outcomes of the actions (the transition function T), the reward function R , and the probabilistic relationships between the agents observations and the states of the environment (the observation function O). The POMDP framework is a systematic approach that uses belief states to represent memory of past actions and observations [14-15].

POMDP provides an elegant and general framework for many realistic problems, but unfortunately are computationally intractable [16-17]. The hierarchical POMDP decomposes the action space into smaller chunks. Since the state is not fully observable, the H-POMDP algorithm is based on action hierarchy [18]. Fig. 2 illustrates the basic concept of the action hierarchy.

Formally, an action hierarchy is a tree, where each leaf is labeled by an action from the action set of POMDP. Each action $a \in A_0$ must be attached to at least one leaf, A_0 is the primitive action.

The H-POMDP is to use the hierarchical action set to replace the full POMDP by a set of smaller POMDPs, which will reduce the computing complexity. Each internal node \bar{a}_i in the action hierarchy is corresponding to a subtask P_i [19]. The subtask is defined as:

- S_i : a state space, corresponding to the full original state space S .
- O_i : an observation space, corresponding to the original observation space O .
- A_i : an action space, containing the children nodes \bar{a}_i .
- π_{P_i} : a local policy, corresponding to the action subset A_i .

Given that the action hierarchy spans a collection of separate POMDP subtasks, in[20] we can independently optimize an independent policy for each subtask, such that we obtain a collection of corresponding *local policies*.

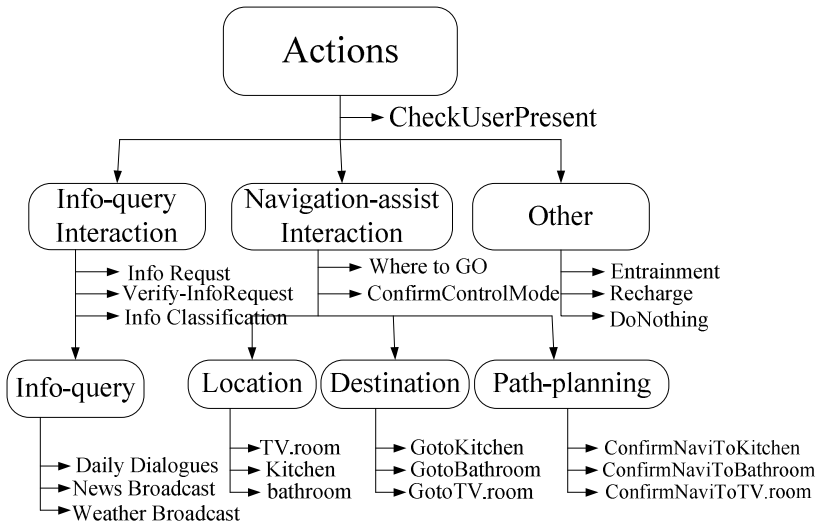


Fig. 2. Hierarchical actions

We adopted four parameters to be adapted by the system. These were speech command, touch-screen input, head position and body posture.

The reward function is based on the information providing by the elderly and the navigation-assist rate in the home environment. An analysis of user’s command of speech, touch-screen and user body position in human-robot interactions report that the evaluation from users had a positive correlation with the information query times and navigation-assist acceptance, and a negative correlation with the head turned to other direction.

Fig. 3 shows a block diagram of reward calculation. The head’s positions and body position of the aged are measured by a camera capture system at a sampling

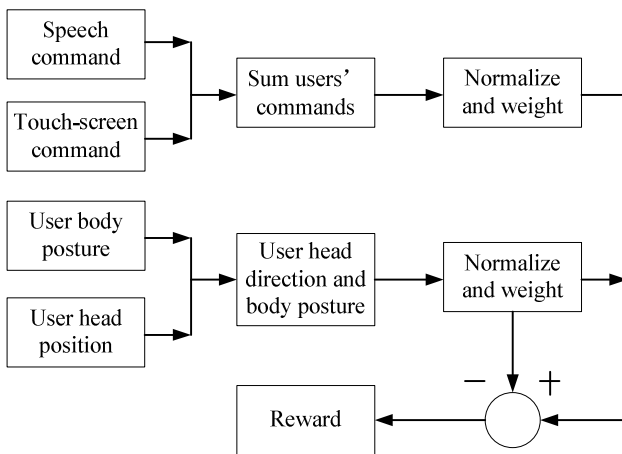


Fig. 3. Block diagram to calculate the reward function

frequency of 56 Hz. The speech command is collected by microphone array in front of the user. The navigation directions are measured by the touch-screen input. The news and weather information query and entrainment are interacted through the speech command.

The reward function R is defined as

$$R = 150 \times (\text{info-query and navi-assist command}) \\ + 225 \times (\text{user's head facing the camera and body parallel to the robot}) \\ - 275 \times (\text{user's head turned to other direction})$$

The contributions of the factors were of equal size as a result [3].

5 Interaction Preference Study

5.1 Interaction Behaviors of the Elderly Companion Robot

There are six interaction behaviors, *Dialogue*, *News-broadcasting*, *Tell-weather*, *GotoKitchen*, *GotoBathroom* and *GotoTV.room*, used in the study. Each behavior takes about 25s to run. During the interaction, the robot tries to provide the *information and assist navigation* of the category to which the behavior belongs. The *information query and navigation-assist* were measured through the interaction interface, user's head position and body posture.

We classified interaction behaviors into three interaction categories: *information-query* (*Dialogue*, *News*, *Weather*); *navigation-assist* (*Kitchen*, *Bathroom*, *TV. room*); and *Other* (*Entrainment*, *Recharge*, *Just-stay-here*).

It also meets the human's head position in a cyclic manner, where the companion robot meets and averts the human's head position in cycles that last average 6s through the camera. The parameter *head-front-ratio* is the portion of each cycle spent meeting the user's head.

The *information-query* controlled which kind information the intelligent wheelchair would display on the screen or voice introduction through the speaker. When it performs behaviors from (a) *dialogue* to (b) *news broadcasting* that require different commands on the part of the user, the companion robot starts the actions after it makes an *information-query* processing.



Fig. 4. The elderly companion robot in a living room

The *navigation-assist* controlled the movement of the robot. If *GotoBathroom* is given, the motion is carried out based on the *location*, *destination* and *path-planning* as the navigation is designed to do.

5.2 The Behavior Adaptation Study

A total of 8 subjects were used in this study. All subjects were students or colleagues of our institute. They were not familiar with the use of the robot, and had no prior experience of interaction with the robot.

We exposed 8 subjects to the behaviors, and let them choose what kind of interaction they were comfortable with for each of these. The robot did not give information or navigation service in the pre-study. There are variations of preferences for each subject within the same class.

The robot was initially placed in the middle area of indoor environment, and the subject was asked to sit in front of the robot and interact with it in a natural way. The robot randomly selects one of the six interaction behaviors. After one behavior finished, it randomly selects the next one. The interaction lasts for 20 minutes.

During the interaction, the H-POMDP behavior adaptation method was running on the robot *Rui*. For the duration of each interaction behavior, or the test of a policy, *Rui* keeps the interaction observation and other parameters according to π_{pi} . The reward function R was calculated for each executed interactive action of the robot using the command input and user head position for the duration of the behavior [3].

The duration starts from just after the robot selects the behavior and it ends at the end of the behavior. A total of ten different parameter combinations were tried before optional policy π_i was calculated and the parameter values updated. The subject did not notice the update of the policy during interaction.

The subject was asked to interact with *Rui*, at the interaction modal that he/she felt was the most comfortable for a representative action for each of info-query and navigation-assist by using behaviors (a) *dialogue*, (b) *News-broadcasting*, (c) *Tell-weather*, (d) *GotoKitchen*, (e) *GotoBathroom*, and (f) *GotoTV.room*, respectively. The subjects were asked to indicate which of the behaviors they felt comfortable with. Few subjects indicated several values for a single parameter, and some indicated preferences between or outside the shown values.

6 Experimental Results

To investigate the advantages of behavior adaption method, we performed experiments using an indoor environment shown in Figure 5. For most of the subjects, at least part of the parameters reached reasonable convergence to stated preferences within 10 min, or approximately ten iterations of the behavior adaptation algorithm.

We performed a half-day of information inquiry experiments using the speech interaction and touchscreen input-output. During these experiments, the robot gave 58 information answer about the weather, news and time.

The *Tell-time* converged in the acceptable range for 6 of 8 subjects. The *News-broadcasting* and *Tell-weather* converged in acceptable range for 7 and 8 subjects,

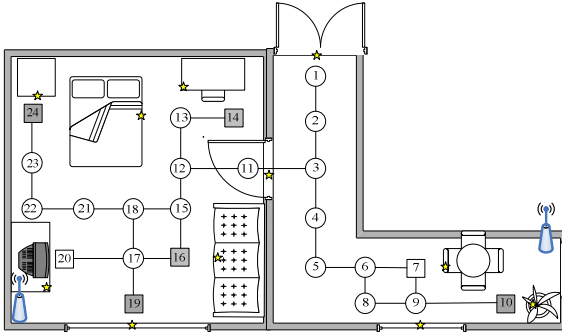


Fig. 5. Indoor experimental environments

respectively. The learned *information-query* is calculated here as the average parameter value during the last 15 min of each study run since the H-POMDP algorithm keeps searching for the optimum value.

The last half-day focused on the navigation experiments. The robot autonomously led 15 full transportation service for 8 different testers. The *GotoKitchen*, *GotoBathroom*, *GotoTV.room*, converged to the values near to selected values for 6, 7 and 8 of 8 subjects, respectively.

Most of the parameters converged in the acceptable ranges; however, it is different in the success rate between different parameters. It is a typical character for the behavior adaptation that parameters having a greater impact on the reward function are adjusted faster.

It is difficult to measure true preferences of the subjects, and the method could neither find the gradient of some parameters nor the direction to the local optimum for some subjects. The reason is that the behaviors of the subject did not display any difference for policies π_i if the current parameter was too far from the preferred values. Thus, different reward functions are needed for people who have different reactions.

There were a few problems that were detected during the experiment. The speech command recognition system were influenced by the background noise, which caused occasional confusion. The problem was fixed using microphone array. An additional problem arose from the power management for long-time work, which was found to be crucial for *Rui's* effectiveness.

We are currently engaged in experimental test in a elderly nursing house, including the old people's operation, interaction with the robot, entrainment and assist navigation. Future experiments will include carrying out longer and more complex scenarios in the nursing house, where the companion robot will carry on the sampling and monitoring the physiological parameters through embedded devices and wireless network.

7 Conclusion

We propose a behavior adaptation method based on H-POMDP that reads interaction signals from the old people, and then adjust interaction output such as daily dialogues,

news and whether broadcasting, motion speed and navigation-assist. The method uses detecting the user's speech command, touch-screen input, head position and body posture as subconscious signals that indicate a user's interaction preference. We have shown that the robot has successfully adapted at least part of the learning parameters to individual preferences for 8 subjects in the study. Although there are still issues to be solved, it is an important step toward building elderly companion robot that is as natural to interact with as humans.

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Appendix

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An Adaptive Information System for an Empathic Robot Using EEG Data

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Abstract. In this paper we introduce a speech-based information system for a humanoid robot that is able to adapt its information presentation strategy to different brain patterns of its user. Brain patterns are classified from electroencephalographic (EEG) signals and correspond to situations of low and high mental workload. The robot selects an information presentation style that best matches the detected patterns. The complete system of recognition and adaptation is tested in an evaluation study with ten participants. We achieve a mean recognition rate of 80% and show that an adaptive information presentation strategy improves user satisfaction in comparison to static strategies.

1 Introduction

Machines play an important role in our everyday lives as matters of communication, work, and entertainment. However, nearly all systems are completely insensitive to the context and actions in their environment. Especially in the interaction with humans, machines neglect the internal states of their users, with the consequence of unnatural interaction, inadequate actions and inefficient user performance. This is especially true for humanoid robots which are designed to integrate into the daily life of their users and therefore need to interact with them in a social and empathic way. One crucial internal state is mental workload. Workload influences how humans process information, their memory span and other factors of cognition which heavily influence the course of interaction between a robot and its user.

This paper describes the setup and evaluation of the adaptive humanoid robot ROBERT. His task is to present gathered information to the user via speech. During the course of one session, the user experiences different levels of mental workload, induced by an external secondary task over which the robot has no control. Therefore, ROBERT uses electroencephalographic (EEG) signals recorded from the user to recognize brain activity patterns. Those brain patterns correspond to conditions of low and high mental workload. This information allows ROBERT to adapt its information presentation strategy to optimally serve the user's needs in the current situation.

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2 Related Work

According to Breazeal [3], the design of sociable robots requires the development of human-awareness, which comprises the concept of empathy, i.e. the understanding of internal states of the human, as an important factor. This information can be used to establish behavior strategies that are adequate for the particular situation and environment. In the last decade, the development of adaptive social robots gained rising attention. Researchers identified a number of user states that have an impact on the optimal interaction behavior of robots. There exist a number of implemented systems which can detect and adapt to those internal states. Most of these systems are evaluated in studies with real humans to show the effectivity of the implemented adaptation measures.

For example, in [10], Torrey et al. evaluated a humanoid robot that adapts its dialog behavior in the kitchen domain to the user's expertise. This is done by modifying the vocabulary and language style of the robot. This way, the robot can act more helpful for novice users and more efficient for expert users. The authors show that this adaptation improves performance measures and subjective perception of the robot. Liu et al. [9] developed a closed loop human-robot interaction framework in a basketball training scenario. They used various features from cardiac activity, heart sound, bioimpedance, electromyographic activity, and body temperature to classify between three levels of anxiety using regression trees. For most of their participants they could show improvements of perceived anxiety and user performance by real-time adaptation of the task difficulty level according to the detected level of anxiety. In [2], Bonarini et al. described a stress recognition algorithm for a rehabilitation robot on the basis of biosignals such as blood volume pressure, galvanic skin response and others. Different stress levels are induced by adding noise to the user's control over the robot. For the discrimination of six different states, the system achieves a recognition rate of 88%. The authors claim that this recognition system can be used to adapt the behavior of the robot, e.g. by adjusting the difficulty of the training program.

There exists a whole corpus of adaptive dialog and information presentation systems outside the domain of humanoid robots. For example, Chen and Verte-gaal [4] proposed a system for improving context awareness for mobile devices. They developed a recognition system for different attentional states of the user. The authors detected two levels of motor activity using EEG signals and two levels of mental load determined by heart rate variability. With their system they could adapt a mobile cell phone to a notification level appropriate to the classified user state. Kohlmorgen, et al. [8] measured workload using EEG while driving for the online adaptation of in-car systems. They used spatial filters and classification by Linear Discriminant Analysis. Their work shows improvements in the reaction time for most subjects due to mitigation of high workload situations for the driver.

To our best knowledge, this paper presents the first implementation and evaluation of an adaptive information system based on EEG in the domain of humanoid robots.

3 Adaptive Information System

The task of ROBERT in this scenario is to provide information to the user about students he met. This information forms a database with multiple entries and consists of attributes like name, id, and telephone number. The information is reported to the user via synthesized speech. The information system is implemented as a finite state machine in a general purpose dialog management engine developed at the Cognitive Systems Lab. It iterates over all entries of the database and reports them one after another.

The style with which information is presented can be adapted according to the brain patterns recognized from the EEG data (see section 4). For that purpose, ROBERT has two different *behavior styles* between which he can switch at any point between two utterances: The first one (called LOW) is selected for brain patterns which correspond to a low mental workload and the second one (called HIGH) is designed for brain patterns corresponding to high workload conditions. While the content which is presented is identical for both, they differ in the style of presentation: LOW focuses on a high information throughput. Therefore, it makes only short pauses between utterances and between different database entries. It also uses a blockwise style for number presentation and combines multiple items for one entry into one utterance, if possible. As we implement the information system for a social humanoid robot, maximized efficiency is not the only goal: ROBERT takes the time to convey the information in complete sentences.

The HIGH behavior style on the other hand is tuned towards situations in which the user is not fully attentive due to a secondary task which he executes in parallel. This results for example in a reduced memory capacity, which is accounted for in this behavior style: Information is presented in a more isolated fashion, only giving one attribute at a time and presenting numbers by reporting each digit separately. To give the user more room to deal with the secondary task, pauses are extended between utterances and even more so between database entries. Time is saved by reducing utterances to the pure minimum, only giving an attribute name and its value.

Table 1. Two behavior styles for information presentation

	LOW	HIGH
pause duration	short	long
number presentation	blockwise	isolated
items per utterance	multiple	one
formulations	complete	concise
example utterances	The name of the next person is Heidi Kundel. Her telephone number is 52-11-66-3.	Heidi Kundel Telephone: 5-2-1-1-6-6-3

The actual strategy of the information system defines how it switches between both behavior styles during the course of a session. For the current experiment, we designed four different strategies:

The ALWAYSHIGH and the ALWAYSLOW strategies define baseline systems which always use one of the two behavior styles, independent of the current state of the user. The EEGADAPTIVE strategy is connected to the EEG-based recognition system and makes use of the recognized brain patterns to select an appropriate behavior (i.e. HIGH when brain patterns corresponding to high mental workload are detected and LOW else). As a gold standard, we also define the ORACLE strategy which is also adaptive but which has direct access to information on the secondary task. Instead of potentially noisy information from EEG data, it selects the optimal behavior for each utterance according to the context information whether the secondary task is currently running or not.

4 Real-Time Brain Pattern Recognition

In order to estimate the level of workload to adjust the ADAPTIVE strategy, we developed a real-time recognition system based on our online EEG workload recognition system [7]. It uses an active EEG-cap (BrainProducts actiCap) to assess the subjects' brain activity by 16 channels with electrodes positioned according to the international 10-20 system. BiosignalsStudio (BSS) forms the input layer for EEG data acquisition, which is a flexible framework for multimodal biosignal recording that has recently been developed at the Cognitive Systems Lab [6].

We derive spectral features between 4 and 45 Hz from one second chunks of EEG signals (overlapping by 0.5 seconds). We then employ Support Vector Machines (SVMs) with radial basis function kernels to discriminate different brain patterns corresponding to the two different mental task demands: with and without secondary task. The resulting binary classifications of the SVM are integrated by averaging over the past 10 seconds (linear temporal smoothing), which increases the stability of the recognition results and provides a task specific load value that expresses smooth trends of the estimated workload. More details on the workload recognition system can be found in [7].

The task load estimation (rational valued) needs to be thresholded to determine the behavior style for the EEGADAPTIVE strategy. Therefore, we determine a subject specific threshold from recognition of the training session, calculated as the mean value of the average task load estimation during the training parts without secondary task, and the training parts with both tasks. If the estimated load level is below the threshold, ROBERT uses the LOW behavior style, if it is above it uses the HIGH behavior style.

To train the recognition system, one training session has been recorded for each subject, consisting of four parts, in the same way as the experimental sessions described in section 5. Each combination of the two behavior styles and the two task conditions (with and without secondary task) is performed during training.

Artifacts are a serious problem for the training of the system. Predominantly eye movement artifacts and muscular artifacts are present in the EEG signals recorded during the experiment. Therefore, we applied a heuristic approach for

artifact detection using thresholds on the signal power and its slope to identify artifacts in each data segment of one second length. Contaminated data segments are dropped and not used in the training of the system.

5 Experimental Setup

To test the different information presentation strategies and the effectivity of the brain pattern recognizer, we designed the following evaluation study: Participants were given the task to manually fill out a form with the information they acquired while listening to the robot. In addition to this primary task, we induced different levels of mental workload by including a secondary task, the participants had to execute in parallel for some parts of the experiments. Sections with secondary task induce a higher mental workload than sections without secondary task and we evaluate whether the system is able to recognize varying brain patterns for both situations and to react accordingly.

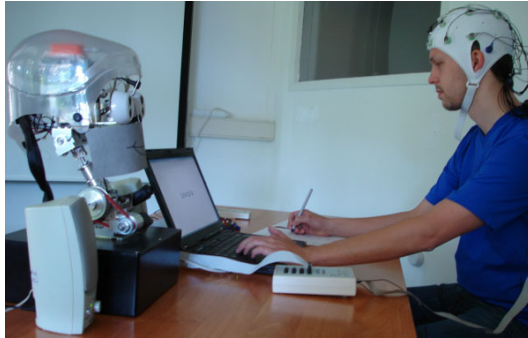


Fig. 1. Recording setup with ROBERT [\[1\]](#) to the left, the computer for the secondary task in the center and a participant wearing an EEG cap to the right

During the experiment, each participant completed five sessions of information presentation. For each session, a different information presentation strategy was used. The first session was specifically designed to collect EEG data for person dependent training of the brain pattern classifier. In subsequent sessions, the strategies ALWAYSHIGH, ALWAYSLOW, EEGADAPTIVE, and ORACLE were applied in random order. ROBERT was present in form of the head of a humanoid robot [\[1\]](#) which talked to the participant. The participants faced paper forms to fill in the information presented by the robot and a computer for the execution of secondary tasks.

Each session consisted of a fixed sequence of two sections without secondary task and two sections with secondary task. Each section approximately lasted one minute and the transition between sections was marked using a signal sound. As a secondary task, the participants processed the cognitive Flanker task in parallel to the robot information task: During the Flanker task, different horizontal arrays of

Table 2. Questionnaire for subjective evaluation of different information presentation strategies. Items marked with * are extracted from the Nasa TLX workload scale.

Q1	How strongly did the robot adapt to the switch between the conditions with and without secondary task?
Q2	How appropriate was the behavior of the robot in conditions without secondary task?
Q3	How appropriate was the behavior of the robot in conditions with secondary task?
Q4	Would you like to work together with a robot with this behavior?
Q5	How do you judge the behavior of the robot concerning “friendliness”?
Q6	How do you judge the behavior of the robot concerning “empathy”?
Q7	How do you judge the behavior of the robot in general?
Q8	Experienced time pressure*
Q9	Experienced accomplishment*
Q10	Experienced effort*
Q11	Experienced frustration*

five arrows are displayed (e.g. <<><<). Subjects respond as quickly as possible to the orientation of the middle arrow by pressing the corresponding left or right key.

Using this setup, ten subjects from age 24 to 29 took part voluntarily in the study and signed a consent form. All of them are students or employees of the Institute for Anthropomatics at Karlsruhe Institute of Technology (KIT).

Along objective scores generated from evaluation of the robot information task and the secondary Flanker task, we also collect subjective judgements of the users. This information allows to evaluate whether any efficiency or quality gains for the tasks were perceived by the user as such, to what degree the users noticed the adaptation efforts of the EEGADAPTIVE and ORACLE strategy and to what degree the different strategies and behavior styles influenced the subjective user experience.

Table 2 lists the questions the participants answered immediately after each session in the experiment. Each item was assigned a 6-point scale. Items Q8 to Q11 were adopted from a subset of the Nasa TLX scale [5] to evaluate the experienced workload in several dimensions.

6 Results

6.1 Recognition Results

The brain pattern recognition system was effectively able to determine the mental workload states of the participants in the experiment. Figure 2 shows an example of the time course of the estimated load level during the EEGADAPTIVE session of one subject. The red horizontal line marks the user specific threshold level. Vertical lines mark regions of different task conditions (i.e. ground truth):

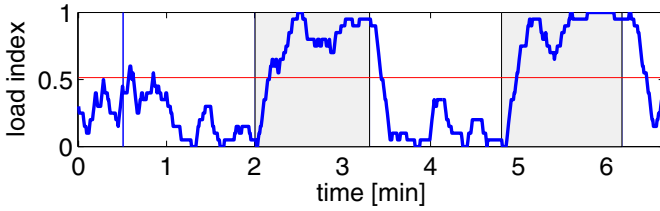


Fig. 2. Task load estimation and threshold for the adapted session of one subject

The sections where the participant processed both, the robot information task and the secondary Flanker task, are marked with gray background color.

The output of the recognizer clearly reflects the different task conditions. To determine the accuracy of the recognition system, we calculate the percentage of recognition outputs where task condition and thresholded workload estimation result match. This is the number of recognition outputs below the threshold, while performing only the robot information task plus the number of recognition outputs above the threshold, while performing both the Flanker task and as the robot information task, divided by the total number of recognition outputs. This results in recognition rates between 69.7% and 90.4% for the EEGADAPTIVE sessions of the 10 subjects with a mean of 80.2% (sd=7.1).

Figure 2 also indicates that there is a small delay of the recognition results as the task demand changes. This can be explained by the temporal smoothing of the recognition system. Furthermore, a switch of the task condition might not have an immediate impact on a person’s mental state. Therefore, the robot’s behavior in the EEGADAPTIVE sessions is different from the behavior in ORACLE sessions due to deferred switching of behavior styles and noisy recognition.

6.2 Task Performance

Table 3 shows task performance metrics for the robot information task and the secondary Flanker task. For the former, we have two different metrics: Correctness rate is the percentage of correctly noted items in relation to the number of completed items, while the completion rate measures the number of completed items divided by the total number of available items. We see that ALWAYSLOW has the highest completion rate due to the high throughput while the ALWAYSHIGH strategy only manages to complete about half of the items. ALWAYSLOW pays this high completion rate with a lower correctness rate. The

Table 3. Average scores for the robot information task and the Flanker task

Item	ALWAYSLOW	ALWAYSHIGH	EEGADAPTIVE	ORACLE
Info: Correctness Rate	85%	96%	96%	94%
Info: Completion Rate	98%	56%	85%	82%
Flanker: Correctness Rate	72%	87%	82%	87%

two adaptive strategies are able to maintain a reasonable completion rate while keeping the correctness rate as high as the conservative ALWAYSHIGH strategy. For the task performance concerning the Flanker task, we see a similar pattern: The performance of the ALWAYSLOW is below the performance of the other strategies which score comparably. We conclude that the adaptive strategies can improve the information presentation by switching behavior styles without hurting task performance.

6.3 Subjective Evaluation

Table 4 summarizes the results of the questionnaires for the subjective evaluation of the behavior of the robot and the experienced mental workload.

Table 4. Results of questionnaires for subjective evaluation of the behavior of the robot and experienced mental workload (standard deviations in parentheses)

Item	Scale from ... (1) to ... (6)	ALWAYSLOW	ALWAYSHIGH	EEGADAPTIVE	ORACLE
Q1	not adaptive – very adaptive	1.6 (0.97)	2.3 (1.70)	4.3 (1.42)	5.5 (0.71)
Q2	not appropri. – very appropri.	4.9 (1.10)	3.8 (1.87)	4.7 (1.42)	4.7 (1.25)
Q3	not appropri. – very appropri.	1.9 (0.88)	4.3 (1.16)	3.7 (1.49)	5.0 (0.82)
Q4	don't work with – work with	1.7 (1.06)	2.9 (0.99)	3.4 (1.26)	4.6 (0.69)
Q7	very bad – very good	2.5 (0.85)	3.8 (0.63)	3.5 (0.92)	4.6 (0.70)
Q5	not friendly – very friendly	3.1 (1.20)	3.8 (0.79)	3.5 (1.35)	4.4 (0.84)
Q6	not empathic – very empathic	2.0 (0.82)	2.6 (1.17)	3.4 (1.17)	4.2 (0.78)
Q8	low pressure – high pressure	5.5 (0.71)	2.9 (1.20)	3.9 (0.86)	3.2 (1.32)
Q9	low accomp. – high accomp.	2.9 (1.20)	3.9 (1.20)	3.6 (1.07)	3.7 (0.95)
Q10	low effort – high effort	5.2 (0.79)	3.3 (1.23)	4.2 (0.92)	3.9 (1.29)
Q11	low frustr. – high frustr.	4.3 (1.06)	2.6 (1.07)	3.0 (1.05)	2.6 (0.52)

The result for item Q1 shows that both strategies which are designed as adaptive (EEGADAPTIVE and ORACLE) are also perceived as such by the participants. This observation is in accordance with the objective effectiveness of adaptivity measured by the recognition rate of the brain pattern classifier (see section 6.1).

For appropriateness of behavior, we differentiate between behavior in absence of a secondary task (Q2) and behavior in presence of a secondary task (Q3). For Q2, the relative drop from the best to the worst strategy is as small as 22.4%. For Q3, i.e. sections with secondary task, the participants more clearly prefer the HIGH behavior: The gap between the worst and the best ranked strategy increases to 62%. We explain this observation by the fact that the benefit of both behavior styles is perceived asymmetrically: While HIGH improves throughput and convenience of the information presentation, LOW can make the difference between successful task completion and mental overload. Still, the order of strategies for Q2 is as expected: ALWAYSLOW has the highest score, EEGADAPTIVE and ORACLE follow with almost identical scores and the slow ALWAYSHIGH strategy is ranked last. For Q3, the EEGADAPTIVE strategy scores slightly worse than ORACLE and ALWAYSHIGH which perform both optimally

in sections with secondary task. EEGADAPTIVE usually switches to the correct strategy but with an delay determined by the window size of temporal integration in the classifier and the fact that a switch of behavior styles only takes place between complete utterances. A quicker classification mechanism, a more flexible adaptation scheme or scenarios with longer sections of constant mental workload will mitigate this effect.

Two items (Q4 and Q7) define a metric for overall quality. Both items are strongly correlated ($r = 0.89$). While we see clear gap between the scores of ALWAYSLOW and the other strategies, the differences between the ALWAYSHIGH, EEGADAPTIVE and ORACLE are much smaller. We explain this observation by the fact that participants mostly rated their ability to cope with the given tasks and that the increased throughput and the more pleasant communication style of the HIGH behavior style did not make a huge difference.

To further investigate how the different strategies were perceived by the participants, Q5 and Q6 asked for how friendly and empathic the behavior during one session was. Q6 reveals that the adaptive strategies (EEGADAPTIVE and ORACLE) were indeed perceived as most empathic and that adaptivity and perceived empathy are correlated ($r = 0.77$ between Q1 and Q6). This indicates that developing adaptive strategies for human-robot communication is an important step towards the implementation of truly social robots. For friendliness, we see no relevant differences in score for the different strategies. We ascribe this to the fact that both behavior styles have aspects that could lead to a perception of friendliness: While HIGH speaks in complete sentences instead of minimal phrases as LOW does, the latter is probably perceived as more considerate in the light of the stressful tasks.

Questions Q8 to Q11 investigate the experienced workload for the different experimental sections. For the dimensions time pressure (Q8), achievement (Q9), effort (Q10), and frustration (Q11), we see a similar pattern: ALWAYSHIGH expectedly performs best and receives scores which indicate relatively low workload. ORACLE gets very close to those bounds. This shows that an adaptive strategy is able to reach near-optimal workload levels while it has the flexibility to use the participant's cognitive resources when available in sections without secondary task. ALWAYSLOW is indisputably much worse in all regards than those two strategies. EEGADAPTIVE approaches the lower workload bound and is (with exception of Q10) closer to the score of ALWAYSHIGH than to the one of ALWAYSLOW. This indicates that EEGADAPTIVE is a reasonable approximation to the ORACLE strategy.

The EEGADAPTIVE strategy depends on the recognition rate of the brain pattern classification to generate satisfying results. This dependency becomes obvious in the higher standard deviation of most items for EEGADAPTIVE than for ORACLE (which works in a deterministic way). The correlation coefficient of the difference between both strategies in overall score Q4 and the recognition rates for individual participants (see section [6.1](#)) is $r = -0.73$ ($p < 0.05$). This observation supports the hypothesis that further improvement of the biosignal classification will directly translate to improvements of user satisfaction.

7 Conclusion

In this paper, we described the design and evaluation of an adaptive speech-based information presentation system for a humanoid robot. This system uses EEG-based brain pattern recognition to switch between two different behavior styles. Those behavior styles are designed to accommodate different conditions of mental workload of the user. An evaluation study with ten participants was conducted. We presented a mean recognition rate of 80% and showed that an adaptive strategy improves user satisfaction in comparison to static ones. We further see that the EEG-based adaptation is a promising approximation to the optimal adaptive strategy.

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Mind Robotic Rehabilitation Based on Motor Imagery Brain Computer Interface

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Abstract. In this paper, a human robot interface called mind robotic rehabilitation is developed for regular training of neurological rehabilitation for stroke patients. The mind robotic rehabilitation is developed based on non-invasive motor imagery brain computer interface (BCI) technology. The use of a spatial filtering algorithm, common spatial pattern (CSP), is proposed for extracting features that maximize the discrimination of two different brain states, left hand movement imagination and right hand movement imagination, during motor imagery of the subject. Furthermore, we find that a feature fusion of feature vectors from both CSP and autoregressive (AR) spectral analysis can obviously improve the performance of the BCI. Quadratic discriminant analysis (QDA) is applied to the combined feature vectors and classifies the vectors into left or right motor imagery category. For evaluation of the proposed BCI, we compare the performance of the proposed method against methods using single feature extraction algorithm, i.e. CSP only or AR spectral analysis only, under an equivalent experiment environment and using the same classifier to estimate the classification accuracy. It is found that feature fusion significantly improves BCI performance.

1 Introduction

Stroke is a neurological disorder that causes severe disabilities or death [1]. Fortunately, stroke patients could partially regain their functional impairment and continue with their activities of daily living with effective rehabilitation [2]. Traditionally, physical therapy is the mainstream rehabilitation for stroke patients [3]. It involves human therapists for assisting stroke patients to recover their motor ability. However, physiotherapies are currently labor intensive and expensive [4]. Furthermore, hospitals and medical specialists

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become insufficient to support these patients suffering from stroke with rehabilitation treatment. A recent innovation in rehabilitation is robot-assisted rehabilitation. Several research studies have reported significant improvements on robotic rehabilitation outcome based on clinical measures [5, 6]. However, most of the designs still remain at the laboratory prototype stage, and the appearance of these rehabilitation robots is not human-friendly. Thus there is increasing demand to develop human-friendly rehabilitation robots for stroke patient to have regular rehabilitation training at home. In this study, we aim to develop a human-friendly and interactive rehabilitation robot based on BCI technology, which is called mind rehabilitation robot.

BCI technology enables the translation of thoughts and intents of humans to actions by machines. Recently, motivated by the advances of BCI technology, BCI-based robotic rehabilitation is introduced [7], which can be called mind robotic rehabilitation. The mind robotic rehabilitation directly translates brain signals that involve motor into commands for controlling the robot and bypasses the normal motor output neural pathways. Hence this mind robot rehabilitation approach provides a means for stroke patients to use motor imagery to help them recover limb movement.

Studies have shown that distinct brain signals such as event-related desynchronization (ERD) or event-related synchronization (ERS) [8] are detectable from EEG for both real and imagined motor movements in healthy subjects [9, 8, 10]; as well as from NIRS [11]. Hence motor imagery brain-computer interface (MI-BCI) [12, 13, 14] which translates the imagination of movements into commands, provides a promising neural communication system for stroke patients who suffer from motor disabilities.

In this study, based on background of motor rehabilitation and robotic rehabilitation, a recently developed mind robot rehabilitation is presented based on a non-invasive motor imagery-based BCI. The major aims of this study are:

- i) A human-friendly rehabilitation robot is developed for stroke patients as an assistive treatment besides labor intensive hospital treatment.
- ii) Feature fusion of features derive of both CSP algorithm and AR spectral analysis is proposed for further classification.
- iii) Both off-line experiment and real-time experiment are performed and evaluated to demonstrate the performance of proposed EEG analysis algorithms.

2 The Training Scenario with Human-Friendly Interactive Rehabilitate Robot

The mind robotic rehabilitation system, which is consist of a BCI system, a human friendly bear robot, and the subject, is shown in Fig. 1. The framework and major function of the robotic rehabilitation system as well as the main modules of the BCI system are briefly demonstrated in Fig. 2.

There are mainly two phases in the implementation of mind robotic rehabilitation. The first stage is the model training phase. This phase aims to obtain the best discriminative parameters, including power band of bandwidth filter, the order of AR model, and projection matrix in CSP algorithm that give the best classification accuracy. The second stage is to perform the real-time experiment based on the model derived from the training phase.



Fig. 1. Mind robotic rehabilitation system

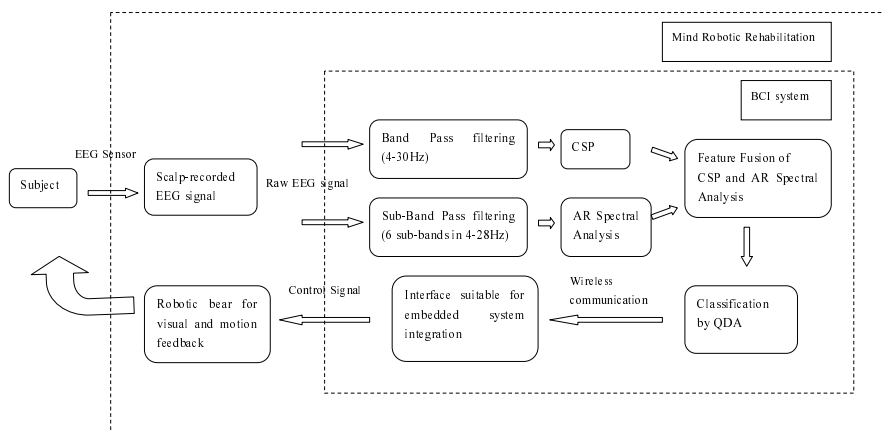


Fig. 2. Framework of mind robotic rehabilitation system

The human-friendly bear robot can interactively act corresponding to the control signal obtained from the BCI system. There are three simple actions - head shaking, left arm shaking and right arm shaking, which correspond to wrong detection of motor imagery, correct detection of left hand movement imagination and right hand movement imagination, respectively.

In conventional BCIs using EEG technology, the lengthy training periods involved for proficient usage can often lead to frustration and anxiety on the part of the user. The proposed interactive robot may solve this problem by making the user more engaged in BCI training during the human robot interaction. This system has the potential to offer an assistive home program as aid to labor intensive and expensive hospital treatment for stroke patients.

3 Data Preprocessing by Band-Pass Filtering

In this work, we adopt several sub-band filters as the data preprocessing for CSP algorithm, which ranges from 4 Hz to 28 Hz [15] with bandwidth of 4 Hz using optimal equiripple FIR filter. The filter which has 1 Hz transition width, 0.1 pass-band ripple and 0.0001 stop-band ripple, is designed using Parks-McClellan algorithm. The raw EEG signal is then convolved with the filter to obtain desired time-series data that contain information in the specified frequency band for further analysis in CSP algorithm.

For the AR modeling, raw EEG data is filtered using optimal equiripple FIR filter with the band width of 4-30 Hz, 0.1 passband ripple, 0.0001 stopband ripple and 1 Hz transition width. The band width 4-30 Hz is selected because it encompasses the alpha and beta frequency bands, which contain rich information on motor activity [16].

4 Feature Extraction and Feature Fusion

In motor imagery-based BCI, numerous methods have been proposed as filters to extract feature patterns from EEG signal. One of the promising and commonly used methods is CSP analysis which uses covariance to design common spatial patterns based on the simultaneous diagonalization of two covariance matrices [17]. Since CSP algorithm is optimal for the discrimination of two populations, it is well suited for discrimination mental states that are characterized by motor imagery. In other words, it utilizes spatial pattern classification to determine spatial filters that maximize the variance of signals of left trials and at the same time minimize the variance of signals of right trials.

However, because the CSP method is very sensitive to artifacts, the motor imagery based BCI system using CSP method will have a high false alarm rate, that's to say, during the on-line operation of the BCI, even when the subject is not responding, the system may give a right or left command. Some preliminary work has solved this problem by performing a weighted spatial averaging of the EEG to reduce the influence of artifacts [18].

In this study, we try to solve this problem in another way by combining two different feature extraction algorithms, the spatial filter CSP and a temporal filtering algorithm AR spectral analysis. The feature fusion of both CSP derived features and AR derived features is utilized for later classification of motor imagery EEG signal in both model training and real time implementation.

4.1 Common Spatial Patterns Analysis

The goal of CSP algorithm is to design spatial filters that lead to new time series whose variances are optimal for the discrimination of two classes of EEG [17]. From technical point of view, the CSP algorithm gives a projection matrix $W^T \in R^{N \times N}$ (N denotes the number of channels), that projects the signal $x(t) \in R^N$ from original sensor space to $y(t) \in R^N$ in a surrogate sensor space, as:

$$y(t) = Wx(t) \quad (1)$$

Usually, we call each row vector $w_j \in R^N$, $j = 1, 2, \dots, N$ of W a spatial filter and each column vector $a_j \in R^N$, $j = 1, 2, \dots, N$ of the matrix $A = W^{-1} \in R^{N \times N}$ a spatial pattern. In [17], the authors showed that two pairs of vectors (w, a) that correspond

to the largest and the smallest eigenvalues for one subject topographically mapped onto a scalp and demonstrated that the interpolation of the value of the components of vectors w_j , and a_j at electrode positions can be somehow related to the neurophysiological understanding of ERD/ERS for motor imagination.

Through a optimized spatial filter, the filtered signal $y(t)$ in (1) have maximized differences in the variance of the two classes of EEG measurements. Let X^1 and X^2 be the data matrices of a short segment of the band-pass filtered EEG signals under two different conditions, i.e., left hand or right hand imagination, respectively. X^1 and $X^2 \in R^{N \times D}$, where N denotes the number of channels, and D denotes the number of samples in a trial in each channel. In training phase, given Q^i trials of EEG signal X^i , $i = 1, 2$ for left hand movement imagination and right hand movement imagination, the corresponding estimates of the average normalized covariance matrices $\Sigma^i \in R^{N \times N}$ can be obtained by

$$\Sigma^i = \frac{1}{Q^i} \sum_{Q^i} \frac{X^i (X^i)^T}{\text{trace}[X^i (X^i)^T]}, i \in \{1, 2\} \quad (2)$$

Then the CSP analysis is given by the simultaneous diagonalization of two covariance matrices.

$$W \Sigma^i W^T = \Lambda^i \quad (3)$$

where Λ^i ($i = 1, 2$), is a diagonal matrix and $\Lambda^1 + \Lambda^2 = I$. Note that $\lambda_j^i = w_j^i \Sigma^i (w_j^i)^T$ ($i = 1, 2$ and $j = 1, 2, \dots, N$) is the corresponding j -th diagonal elements of Λ^i , and $\lambda_j^1 + \lambda_j^2 = 1$, since λ_j^i is in fact the variance of y_j in condition i in the corresponding surrogate space of x_j , a large value of λ_j^1 close to one indicates that the corresponding spatial filter w_j yields high variance in condition 1 and a low variance in condition 2, and vice versa.

Technically, the simultaneous diagonalization can simply be achieved by solving the generalized eigenvalue problem

$$\Sigma^1 W^T = \Lambda \Sigma^2 W^T \quad (4)$$

using the command $[W^T, \Lambda] = \text{eig}(\Sigma^1, \Sigma^2)$ in MATLAB, where Λ is a diagonal matrix of generalized eigenvalues λ_j , and W^T is a full matrix whose columns are the corresponding eigenvectors to fulfill (4). Since $\lambda_j = \lambda_j^1 / \lambda_j^2$, based on the former analysis, the largest and smallest diagonal elements in Λ are corresponding to the spatial filters which keep most discriminative information.

For classification, the features of each single-trials are calculated as the log-variance in CSP projected signals. Since the largest and smallest diagonal elements in Λ are corresponding to the spatial filters which keep most discriminative information, in other words, the first r and the last r rows of W would contain the most discriminative information, only $2r$ (r is usually chosen as 2) patterns are used. The variance features are approximately chi-square distributed, and taking logarithm makes them similar to Gaussian distributions so that a linear classifier can be used for classifying the features. Therefore, feature vector of t -th trial EEG signal is generated as follows:

$$F_t = \log \frac{\text{var}[y_j(t)]}{\sum_j \text{var}[y_j(t)]}, j = 1, \dots, r, N - r + 1, \dots, N \quad (5)$$

4.2 Autoregressive Spectral Analysis

Besides CSP algorithm, attenuation or increase of localized neural rhythmic due to actual and imagined motor activity can also be detected by observing the change in band power [19, 20]. Before the band power spectral analysis, the raw EEG time series is convolved with the band-pass filter mentioned in Section 3. The estimate Power Spectral Density (PSD) of the filtered signal is then calculated through autoregressive (AR) spectral analysis. Filtering before estimating its PSD is important because noisy data (contains high frequency component, i.e., more than 30 Hz) will affect the AR modeling accuracy.

A proper order of the AR model should be examined to ensure good modeling quality. In this study, AR model of 8 is selected and it is consistent with other works [21, 22, 21].

Yule-Walker method [23] is used to estimate the AR parameters. The estimated AR parameters are then used to calculate estimated PSD of the EEG signal. The power spectrum is given by

$$P_{xx}(f) = \frac{\sigma^2}{\|1 + \sum_{k=1}^p a_p(k)e^{-j2\pi fk}\|^2} \quad (6)$$

where $a_p(k)$ denotes the estimates of the AR parameters obtained using Yule-Walker method, σ^2 is the variance of the white noise, and p denotes the order of AR model.

The discriminative band normally lies within 8 to 25 Hz [10]. Since the most important brain activities during motor imagery are within the α and β range, the power spectral density is calculated in 4 frequency ranges: 8 – 10 Hz, 10 – 12 Hz for α ; and 20 – 24 Hz, 24 – 28 Hz for β . Let d_0 represents the beginning of band power, bw represents the selected bandwidth, P_{xx} represents the power spectral density estimation obtained using Yule-walker's method. The selected range of band power P_b for one channel EEG can be calculated as

$$P_b = \sum_{d_0}^{d_0+bw} P_{xx} \quad (7)$$

The band power P_b is used as feature for classification, and the feature vector consists of P_b of four different frequency band range in two channel of EEG signal, C3 and C4. As such, 8 features in total are extracted from one trial of EEG signal. This 8-elements feature vector is then appended to the $6 \times 2r$ -element feature vector F_i derived from CSP algorithm to form a fused feature, which can be denoted as $F_{combined}$.

5 Classification by Quadratic Discriminant Analysis

Using the combined feature vector, $F_{combined}$, QDA [24] is used for classification. Quadratic discriminant analysis (QDA) is closely related to linear discriminant

analysis (LDA), the difference is in QDA there is no assumption that the covariance of each of the classes is identical.

The classifier works by estimating the probability that an observation, x , belongs to each class, k , and then selects the class with the highest probability. The posterior probability of each class k is given as

$$Pr(k) = \frac{f_k(x)\pi_k}{\sum_{j=1}^k f_j(x)\pi_j} \quad (8)$$

where $f_k(x)$ is the probability density function of data in class k , and π_k is the prior probability of class k .

Assume all the classes have multivariate normal distribution, the probability density function of data in class k is given as,

$$f_k(x) = \frac{1}{(2\pi)^{p/2} \|\Sigma_k\|^{1/2}} e^{-\frac{1}{2}(x-\mu_k)^T \Sigma_k^{-1} (x-\mu_k)} \quad (9)$$

where p is the dimension of x , $\mu_k = \sum_{x_i \in k} \frac{x_i}{N_k}$ is the Gaussian mean of data in class k , and covariance matrix $\Sigma_k = \sum_{x_i \in k} (x_i - \mu_k)(x_i - \mu_k)^T$.

The prior probability of class k can be estimated as

$$\pi_k = \frac{N_k}{N} \quad (10)$$

Ignore the same denominator of posterior probability for each class, if we take the log of the numerator and ignore the constant $(2\pi)^{p/2}$ in the density function, we can get the quadratic discriminant function:

$$\delta_k(x) = -\frac{1}{2} \log |\Sigma_k| - \frac{1}{2} (x - \mu_k)^T \Sigma_k^{-1} (x - \mu_k) + \log \pi_k \quad (11)$$

Then, the class for a observation x can be selected as the class with the highest score according the the discriminant function.

6 Experimental Evaluation

This section reports an empirical evaluation of the proposed EEG analysis algorithms for BCI-based mind robotic rehabilitation. The EEG analysis algorithms are evaluated by both off-line experiment using some well-known open source data and a real-time experiment on the human-friendly interactive rehabilitation robot developed.

6.1 Data Acquisition

The EEG signal was acquired at sampling frequency 128 Hz by a wireless EEG acquisition system, Bioradio150 Kit by Clevedmed. Three electrodes were positioned at C3, C4 and CZ according to the international 10-20 standard electrode placement. There were 200 trials for training and each trial lasted for 9 seconds with a cue of left or right arrow to remind the subject. After training, real-time testing was performed based on the data

analysis model obtained from the training phase. For each trial, a 1 second windowing was used. These time segments are well-chosen so that each segment contains most of the useful information. It should neither be too long to be unstationary nor too short to have incomplete information.

6.2 Off-Line Training Experimental Results

We compare the classification accuracy in the training phase between CSP method, AR spectral analysis method, and the feature fusion with both CSP features and AR feature. A 10×10 fold cross validation is used to obtain the classification accuracy, as shown in Fig. 3 and Table 1. To evaluate our method, we also use dataset III from BCI competition II 2002 [25] for off-line training experiment.

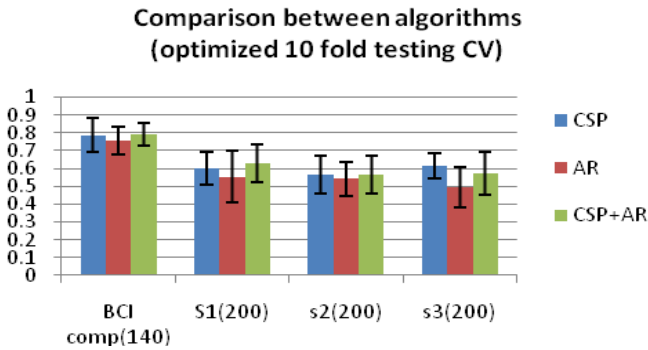


Fig. 3. Classification accuracy for off-line training

Table 1. The classification accuracy (mean ± standard deviation) in off-line training

Subject (number of training trials)	CSP only	AR only	CSP+AR
subject 1 (200)	0.5998 ± 0.0913	0.5543 ± 0.146	0.6293 ± 0.1061
subject 2 (200)	0.5643 ± 0.1045	0.5408 ± 0.0979	0.5641 ± 0.1048
subject 3 (200)	0.6146 ± 0.0728	0.496 ± 0.1119	0.5747 ± 0.1192
BCI competition 2, dataset III	0.7857 ± 0.0952	0.7571 ± 0.0768	0.7929 ± 0.0625

The cross validation results suggest that the fusion method does provide an improvement in classification accuracy as shown in Fig. 3 and Table 1.

6.3 Real-Time Testing Experimental Results

A comparison of the classification accuracy in the real-time testing phase between CSP method, AR spectral analysis method and the feature fusion with both CSP features and AR feature is also performed. The testing data directly use the data analysis model derived from the training phase to obtain the label of left/right hand movement imagination. The results are shown in Fig. 4 and Table 2.

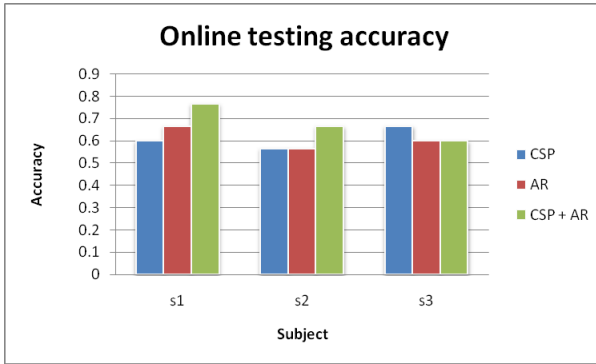


Fig. 4. Classification accuracy for real-time testing

Table 2. The real-time testing accuracy

Subject (Number of test trials)	CSP only	AR only	CSP+AR
subject 1 (30)	0.6	0.6667	0.7667
subject 2 (30)	0.5667	0.5667	0.6667
subject 3 (30)	0.6667	0.6	0.6

The results suggest that the fusion method also outperforms single feature extraction algorithm in real-time testing phase as shown in Fig. 4 and Table 2.

7 Conclusion

In this paper, a human robot interface called mind robotic rehabilitation was developed based on BCI technology for regular training of neurological rehabilitation for stroke patients. A human-friendly interactive robot was used as a visual feedback for BCI to make the user better engaged into rehabilitative training during the human robot interaction. Feature fusion of CSP algorithm and AR spectral analysis was proposed. QDA was used as classifier to classify the combined feature vectors. Off-line experiment and real-time implementation were performed using some well-known open source data and real-time recording data. The experimental results demonstrated that feature fusion significantly improved BCI performance.

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COSA Finger: A Coupled and Self-Adaptive Under-actuated Unit for Humanoid Robotic Hand

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Abstract. Aiming to overcome the serious disadvantages of two kinds of under-actuated fingers: coupled finger and self-adaptive finger, this paper proposed a novel grasping mode, called Coupled and Self-Adaptive (COSA) grasping mode, which includes 2 stages: firstly coupled and then self-adaptive grasping. A 2-joint COSA finger with double tendons mechanisms (called COSA-GRS finger), is designed based on the COSA grasping mode. The new finger unit has the advantages of coupled finger and self-adaptive fingers. Using the COSA finger, a humanoid multi-fingered hand can be designed. The new hand will be more similar to human hand in appearance and actions, able to more dexterously and stably grasp different objects than tradition coupled or self-adaptive under-actuated hands.

Keywords: Multi-fingered hands, Under-actuated finger, Coupled finger, Self-adaptive finger, Grasping mechanism.

1 Introduction

Robot hands consist of a palm and several fingers. According to different working principles and grasping functions of fingers, robot hands are divided into three types:

- 1) Clamp in industry, whose fingers have no joint or they have rigid pseudo joints.
- 2) Dexterous hands, whose fingers have multiple active joints driven by actuators. For example, Utah/MIT Hand ^[1], DLR-II Hand ^[2], Robonaut Hand ^[3], Shadow V5 Hand and domestic BH series hands by BUAA (Beijing University of Aeronautics and Astronautics) and HIT series hands by HIT (Harbin Institute of Technology).
- 3) Under-actuated hands, in which the number of actuators of its fingers is less than the degrees of freedom (DOFs).

Traditional under-actuated (UA) finger mechanisms are divided into two main kinds: coupled UA finger and self-adaptive UA finger. General under-actuated fingers have two types: coupled UA finger and self-adaptive UA finger.

(1) Coupled UA fingers. For example, a coupled finger with 2 joints. If the proximal joint revolves, the distal joint will revolve by an angle with a fixed proportion of the proximal joint. A fixed rotating relationship between its joints is designed to reduce the number of actuators. The ratio of rotation angles between coupled phalanges is set to be fixed during mechanical design.

Most designs are used in prosthetics. Pioneer design includes Southampton Hand ^[4], MANUS-Hand ^[5] and TBM Hand ^[6].

Coupled fingers have advantages: it is fit for grasping a small object with pinch style and the motion of the fingers is similar to human fingers. The finger imitates the human finger as naturally as possible with less complex control. However, coupled UA fingers are not able to closely wrap the grasped object and it cannot self-adapt different shapes of objects. The upper phalanges may not touch the object when the lower phalanges are blocked by the object. Thus this type of hands is unable to be used as universal grippers.

(2) Self-adaptive UA fingers. The fingers can self-adapt the shapes and sizes of the grasped objects. The adaptation is designed as a main function. The grasp range is enlarged and the grasp stability is improved.

SARAH Hand ^[7, 8], the under-actuated hand by HIT ^[9], LARM Hand ^[10], the under-actuated hand by BH Univ. and TH-3R Hand ^[11] belong to this approach.

Though the grasping capability is improved comparing to the coupled UA hand, the passive adaptive UA hand has some disadvantages either. Self-adaptive UA fingers cannot bend the middle joints before contacting the grasped object, which limits its grasping ability and its actions of grasping small objects are not similar to human fingers.

Combining of the two approaches will be an effective method to solve the problems for improving the grasping performance. A robot hand with two kinds of UA mechanisms has been addressed ^[12].

The scheme only put a kind of traditional coupled finger and a kind of traditional self-adaptive finger as a serial line to realize a new finger with 3 joints. The mechanism from the first joint to the second joint is self-adaptive mechanism. The mechanism from the second joint to the third joint is coupled mechanism. This is a serial style of two kinds of mechanisms, does not really combine the two kinds into one set of mechanism. The finger does not eliminate the shortages of the single coupled fingers and self-adaptive fingers.

Aiming to resolve the problems existed in two main kinds of fingers, a novel concept of Coupled and Self-Adaptive (COSA) grasping mode is proposed in this paper, a parallel coupled and self-adaptive mechanism is designed to reach this purpose.

2 Coupled and Self-Adaptive (COSA) Grasping

The Coupled and Self-adaptive Grasping procedure consists of two basic stages explained as below and Figure 1 display its mode.

(1) In the first stage, coupling grasp stage, the distal joint rotates the equal angle θ as the proximal joint rotates when drives from the base, as the coupling scale is 1:1 and the procedure continues until object touches the phalange, shown in Figure 1a. There are three modes according to the different touching points.

The coupling grasp stage is an important process with pre-bending, similar to human finger's movement, and in this stage the finger will pre-bend before it touch the object for the final grasp of the object.

(2) In the second stage, self-adaptive grasp, the proximal phalanx touches the object earlier and the grasping process will continue after the proximal phalanx contact the object with the distal phalanx rotating only.

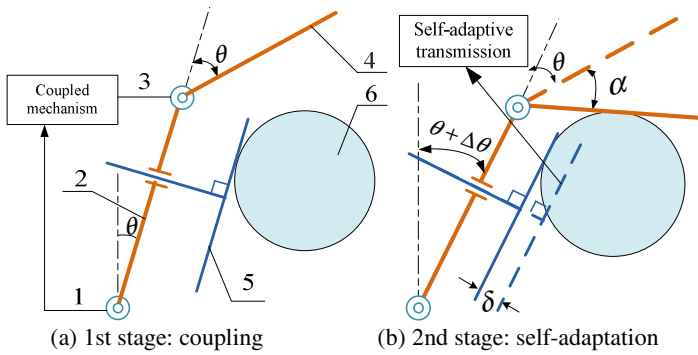


Fig. 1. Two stages of COSA grasping mode. 1-proximal joint; 2-proximal phalanx; 3-distal joint;4-distal phalanx; 5-receiver (movable slider); 6-the grasped object.

The most substantial element to complete this grasping process is a movable prominent slider which is placed in the slot of the proximal phalanx with a small free moving range of 5mm or so. The slider connects the proximal joint with the distal joint and is available to glide when it contacts the object earlier than the distal phalanx, changing the coupling grasp into the self-adaptive grasp.

During the self-adaptive grasping process, the distal phalanx rotates a larger angle than the proximal phalanx due to the slider gliding into the proximal phalanx and the distal phalanx keeps rotating until it touches the object ultimately(the procedure is shown in Figure 1b).

Therefore the self-adaptive grasp process takes place of the coupling grasp when the proximal phalanx contacts the object before the distal phalanx does, which causes the slider to glide and break the coupled transmission between the distal and proximal phalanx.

3 Design of COSA-GRS Fingers

3.1 The COSA-GRS Finger with 2 Joints

A 2-joint COSA finger is designed for realizing coupled and self-adaptive grasping mode. The principle of the finger is shown in Figure 2. In Figure 2, the finger mainly consists of a DC motor mounted in a base 1, a proximal phalanx 3, a lower gear 2, a lower rack 4, a lower slider 5, an upper slider 6, an upper rack 7, an upper gear 8, a distal phalanx 9, a compression spring 10.

The special mechanical design is shown in Figure 3.

As is shown in Figure 2 and Figure 3 above, the proximal phalanx is installed on the base with a proximal joint-shaft connecting the two parts and connects with the distal phalanx with a distal joint-shaft, which is fixed with the distal phalanx, between them. The lower gear, meshing with the lower rack that fixed with the lower slider, is set on the proximal joint-shaft and fixed with the base. Similar to the lower gear, the upper gear, meshing with the upper rack that fixed with the upper slider, is set on the distal

joint-shaft and fixed with proximal phalanx. The two sliders have a parallel moving direction and are both installed in the slot of the proximal phalanx. The plane surfaces of the two sliders contact with each other when the finger is straight and this transmission makes the upper phalanx rotate by the lower slider gliding in to the lower phalanx and thus leading the upper slider to move inside. A compression spring is set between the upper slider and the proximal phalanx and a torsion spring, whose two sides connect the joint-shaft and the phalanx, is installed on the proximal joint-shaft.

A humanoid robot hand with five COSA-GRS fingers can be designed with the COSA-GRS finger unit mentioned above.

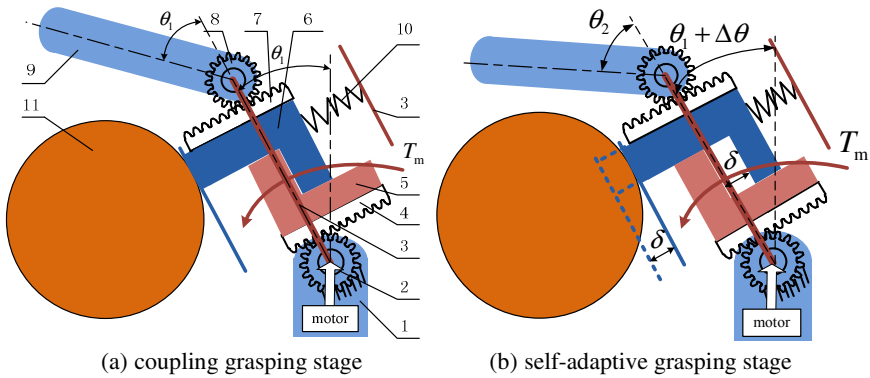


Fig. 2. The principle of the COSA-GRS finger unit

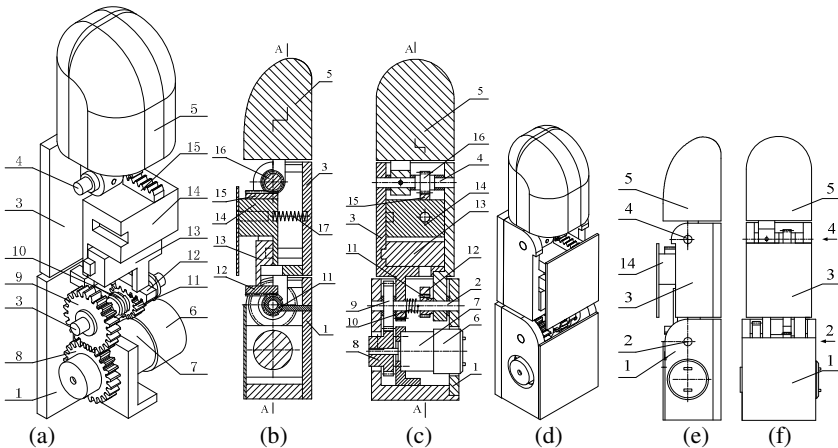


Fig. 3. Mechanical design of 2 joints COSA-GRS finger. 1-base; 2-proximal joint-shaft; 3-proximal phalanx; 4-distal joint-shaft; 5-distal phalanx; 6, 7-DC gear motor; 8, 9-gear; 10-torsion spring (adjusting grasping force); 11-lower gear; 12-lower rack; 13-lower slider; 14-upper slider; 15-upper rack; 16-upper gear; 17-compression spring.

3.2 Grasping Principle of the COSA-GRS Finger

Figure 4 illustrates the 2-joint finger grasping process and Figure 4(a) shows the initial state of the finger. The two phalanges are parallel due to the pressure of the spring between the phalanx and the upper slider.

The two grasping stage is explained as below:

a) The coupling grasping stage: The proximal joint-shaft rotates driven by the torque transmitted from the motor and drives the proximal phalanx to rotate by the force transmitted through the torsion spring. Then the finger bends and the lower rack moves inside the phalanx with the meshing gear rotating at the same time. The lower slider fixed with the phalanx with the lower rack glides and causes the upper slider to move. Thus the distal phalanx was driven by the gear meshed with the upper rack that glides together with the upper slider and this process keeps acting until the upper slider touches the object (shown in Figure 4a-b-c). It is necessary to mention that rotating angles of the two phalanges are equal because of the size of the two gears are the same.

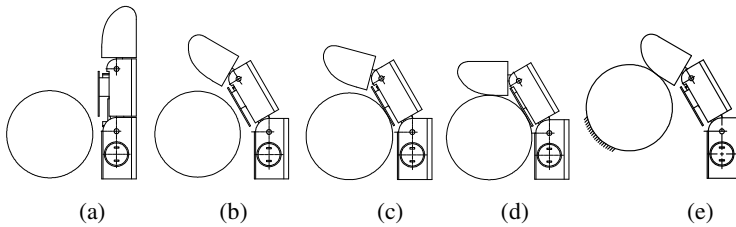


Fig. 4. Grasping process of 2 joints COSA-GRS finger

b) The self-adaptive grasping stage: When the grasping process comes to the step as Figure 4(c) shows, the upper slider stops gliding and is bunted into the phalanx by the grasped object. Then the proximal phalanx keeps rotating a relatively much smaller angle than the distal phalanx does, due to the distance between the upper slider and the phalanx is larger than the lower slider and the phalanx, in what situation the upper rack, gliding together with the upper slider, drives the small upper gear (for instance, the diameter is 5mm) to rotate faster than the lower gear, which will cause the contacting surface of the two sliders separates, until the finger wraps the object and the process finishes ultimately. That is to say, after the upper slider contacts the object, the distal phalanx starts to rotate faster than the proximal phalanx and this contribute to the second stage (the self-adaptive grasping stage) begins. During this stage, the distance between the two plane surface mentioned before becomes larger and larger with the two racks, which causes the gears rotates at different speed and results in the different angles the distal and the proximal phalanx rotates. As the process didn't stop until the two phalanges both touch the object, it can be always efficacious for the finger to fit different shapes and sizes. It can be known from the explain above that the rotating angle of the distal phalanx is no longer equal to that of the proximal phalanx but the finger is capable of fitting varied objects.

In addition, the pinch can also be acted when the grasping process is finished with the distal phalanx touches the object only (illustrated in Figure 4e).

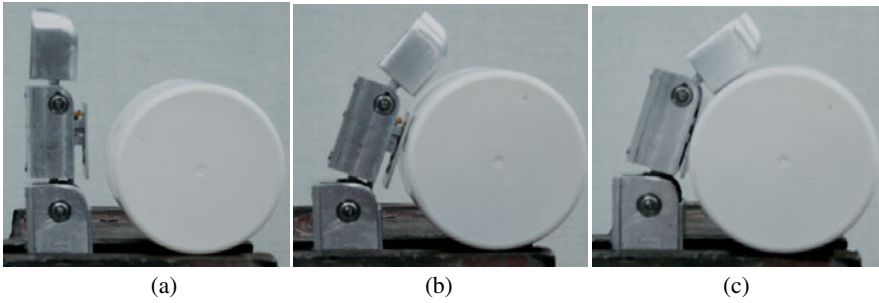


Fig. 5. The real grasping process of COSA-GRS finger

The coupling grasping and self-adaptive grasping are both realized in the finger. The motion process of opening the finger has the same principle with the grasping motion process addressed above. The real grasping process of COSA-GRS finger is shown in Figure 5.

4 Decoupling Analysis of the COSA-GRS Finger

A COSA finger combines the coupling motion and self-adaptive motion. The two motions are generally contrary. So how to decouple the coupled mechanism when the finger touching the grasped object is the successful key of the design of COSA finger. The cause of that the COSA-GRS finger can naturally decoupled its coupled mechanism when the finger touching the grasped object is illustrated in detail here. The analysis is deduced based on the situation shown in Figure 6 with relating geometric parameters.

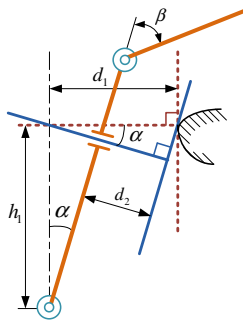


Fig. 6. Decoupling analysis sketch of the COSA-GRS finger

Where,

d_1 : the distance between the edge of the upper slider and the center line of the finger before rotating, mm

d_2 : the distance between the edge of the upper slider and the center line of the finger after rotating, mm

r_1 : the radius of the lower gear, mm
 h_1 : the force arm of f_1 with respect to the center of the lower gear, mm
 α : the rotation angle of the proximal phalanx relative to the base, °
 β : the rotation angle of the distal phalanx relative to the proximal phalanx, °
 One has

$$d_2 = d_1 \cos \alpha - h_1 \sin \alpha \cos \alpha \tag{1}$$

Let

$$\Delta d = d_1 - d_2 \tag{2}$$

$$\Delta d = d_1 - d_1 \cos \alpha + h_1 \sin \alpha \cos \alpha \tag{3}$$

From the three equations one can conclude:

$$\Delta d - r_1 \alpha \geq 0 \tag{4}$$

Eq. (4) shows the condition that the decoupling is successful completed. We can see there are five independent parameters in the equation. To throw light on the relationship of the parameters, the number of independent parameters should be reduced. r_1 is given first. Given h_1 , is expressed as a function of and d_1 shown in Figure 7.

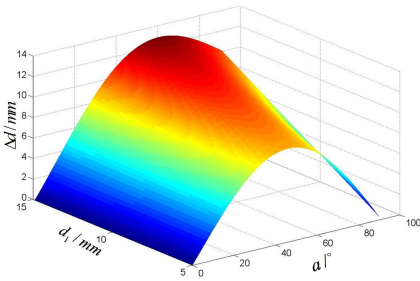


Fig. 7. The relation among Δd , d_1 and α

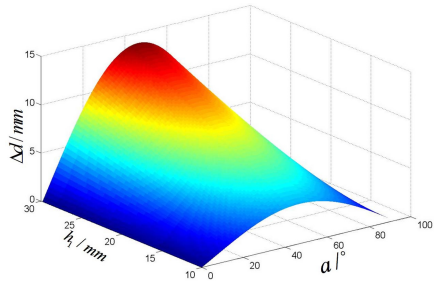


Fig. 8. The relation among Δd , h_1 and α

Given d_1 , is expressed as a function of and h_1 shown in Figure 8.

The Figure 7 and 8 show that the decoupling is successful in the whole range of the parameters. This proves the design of the finger is not only feasible but also superior in the term of decoupling function which is crucial to the combination of coupling motion and self-adaptive motion.

5 Force Analysis of the COSA-GRS Finger

Figure 9 illustrates the force analysis of the 2-joint COSA finger when grasping an object.

To explain the Figure 9, N_1 : the pushing effect that the object has on the proximal phalanx, N

- N_2 : the pushing effect that the object has on the distal phalanx, N
- N_s : the pushing effect that the compression spring has on the upper slider, N
- F_m : the pushing effect that the upper rack has on the upper gear, N
- F_n : the pushing effect that the upper gear has on the upper rack, which is equivalent to F_m but has the opposite direction, N
- R : the radius of the gear, mm
- L : the proximal phalanx's length, mm
- M : the motor's torsion, Nm
- l_1 : the moment of N_1 about the center point of the lower gear, N
- l_2 : the moment of N_2 about the center point of the upper gear, N
- l_s : the dimension of the compression spring has changed, mm
- ε : the movement of the upper slider, mm
- k : the coefficient of the compression spring, N/mm
- α_1 : the proximal phalanx's rotating angle relating to the base, °
- α_2 : the distal phalanx's rotating angle relating to the proximal phalanx, °

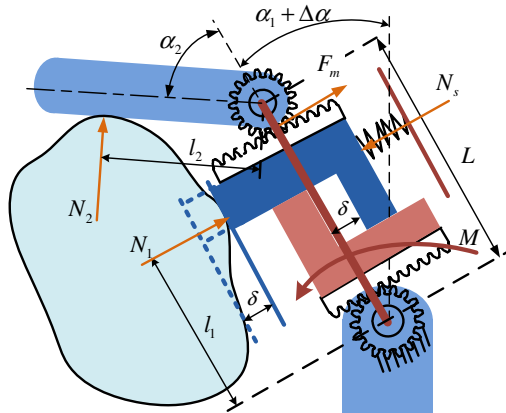


Fig. 9. Force analysis of the COSA-GRS finger at the 2nd stage

The equations can be obtained from the analysis ignoring the friction and the moving of the finger.

Relating to the center of the lower gear:

$$M = N_1 l_1 + N_2 (l_2 + L \cos \alpha_1)$$

Relating to the distal phalanx:

$$N_2 l_2 = F_m R$$

Relating to the upper slider:

$$F_m + N_s = N_1$$

Relating to the spring:

$$N_s = k l_s$$

Relating to the moving distance of the upper slider:

$$\varepsilon = (\alpha_1 + \alpha_2)R \quad (5)$$

The below equations can be obtained from the five equations:

$$N_1 = \frac{Ml_2 - k(\alpha_1 + \alpha_2)l_1l_2R}{l_1l_2 + R(l_2 + L\cos\alpha_2)} + k(\alpha_1 + \alpha_2)R$$

$$N_2 = \frac{MR - k(\alpha_1 + \alpha_2)l_1R^2}{l_1l_2 + R(l_2 + L\cos\alpha_2)} \quad (6)$$

When $M=4500$ mNm, $R=3.5$ mm, the range of α_1 and α_2 from $0\sim 90^\circ$, $L=40$ mm, $k=0.5$ N/mm, $l_1=20$ mm, $l_2=10$ mm, then the relationships of N_1 , N_2 , α_1 and α_2 are shown in Figure 10. The conclusions from these figures are listed below.

- 1) The N_1 and N_2 will change slightly with α_1 increasing.
- 2) The N_1 and N_2 will increase distinctly with α_2 increases.
- 3) The N_1 and N_2 will always keep positive in any case, and they are enough large to grasp objects stably.

These simulation results show the COSA-GRS finger which can grasp objects stably is effective.

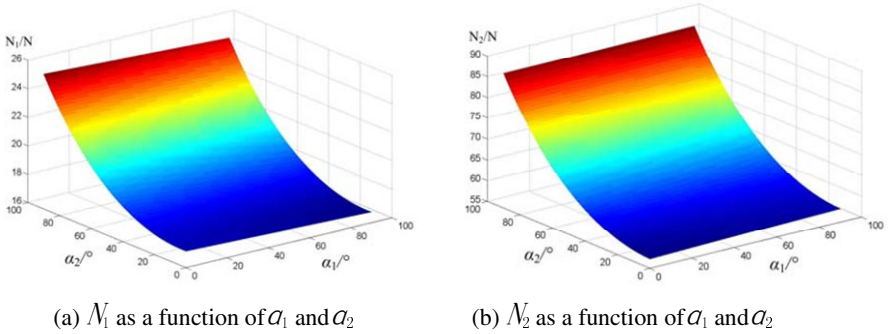


Fig. 10. Force analysis results of the COSA-GRS finger

6 Conclusion

A Coupled and Self-Adaptive (COSA) grasping mode is proposed which includes two stages: firstly coupling grasping stage and secondly self-adaptive grasping stage. The 2-joint COSA finger with double gear-rack-slider mechanisms (COSA-GRS finger) is designed. The simulation results show that the designed finger is effective.

Using the COSA finger, a humanoid multi-fingered hand can be designed. The new hand will be more similar to human hand in appearance and actions, able to more dexterously and stably grasp different objects than tradition coupled or self-adaptive under-actuated hands.

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A Humanoid Robot Upper Limb System with Anthropomorphic Robot Hand: GCUA Hand II

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Abstract. Gesture-changeable under-actuated (GCUA) function is presented to make robot hand grasp objects dexterously and achieve humanoid manipulations with low dependence on control system. Based on GCUA function, GCUA Hand II is developed, which has 5 fingers and 14 DOFs. All the fingers use similar tendon mechanisms to achieve GCUA function which includes traditional under-actuated (UA) grasping motion and special pre-bending (PB) motion. With GCUA Hand II, a humanoid robot upper limb system is developed, which has two 3-DOF arms actuated by stepper motors and two 14-DOF hands actuated by DC motors. The control system includes four parts: computer, motion controller based on FPGA, driver module, and user module, which can control the upper limb system to do various movements dexterously and exactly. The control system and spatial motion program are designed. This system has a great prospect in the field of robotics and rehabilitation engineering.

Keywords: humanoid robot, robot hand, upper limb, self-adaptation, gesture-changeable under-actuated function.

1 Introduction

The great developments in robotics have recently led researchers and robot designers to take interest in humanoid upper systems with dexterous robotic hands, whose terminals can arrive any point in a large space and grasp various objects dexterously. Most industrial robots use grippers or tools as their terminals to grasp and manipulate, however, humanoid robots need upper limbs with artificial hands, which are expected to achieve typical human tasks in non-specific environment^[1]. In recent years, many different robot upper limbs have been designed and applied. For instance, the active upper-limb exoskeleton robot systems have been proposed for rehabilitation and power assist^[2-3].

As the terminal of humanoid robot upper limb, anthropomorphic robot hands, including dexterous hands and under-actuated hands, are taken into account. M. A. Saliba and M. Axiak have designed a compact and dexterous robot hand^[4]. All of the actuators and sensors of the hand are located remotely from the fingers, which makes the hand small enough. MP joint and PIP joint of each finger is driven by an actuator respectively, and the cable and pulley coupling mechanism between PIP joint and DIP joint makes these two joints rotate synchronously. The hand can achieve a lot of humanoid motions dexterously.

I. Yamano and T. Maeno used ultrasonic motors and elastic elements to develop a 5-fingered robot hand^[5]. Index finger, middle finger, ring finger and little finger use three ultrasonic motors to drive four joints respectively, and the thumb uses three ultrasonic motors to drive three joints. The hand with twenty joints can perform stable and compliant humanoid grasping motion.

W. Zhang and D. Che designed a dexterous hand: GCUA Hand, which has 5 fingers and 15 DOFs^[6-7]. Based on a novel grasping function: gesture-changeable under-actuated (GCUA) function, the hand can grasp different objects self-adaptively and pose many humanoid gestures.

SKKU Hand II with a finger-tip tactile sensor is designed by B. Choi, S. Lee, H. R. Choi, et al.^[8] which has a thumb and three fingers. The thumb has 4 joints with 4 DOFs, and each finger has 3 joints with 2 DOFs. Moreover, the finger-tip tactile sensor, based on polyvinylidene fluoride, is flexible enough to feel 3-dimensional force.

N. Tsujiuchi, T. Koizumi, S. Shirai, et al designed balloon-type pneumatic actuators, and used those actuators to develop a 5-fingered robot hand. The hand has a movable range closed to a human being's hand, which can hold a variety of objects^[9].

Other examples of robot hands are Utah/MIT Hand^[10] which is designed by S. Jacobsen, E. Iversen, D. Knutti, et al, DLR Hand^[11] which is designed by H. Liu, P. Meusel, N. Seitz, et al.

In this research, a new multi-fingered hand is designed, which uses tendon mechanisms and elastic elements to achieve GCUA function. Moreover, two 3-DOF robot arms are developed to make the multi-fingered hand (as the terminal) feel easy to touch any point in a large space. With the combination of robot hands and arms, the system can achieve humanoid manipulations like people. The control system of the humanoid robot upper limb is also designed.

2 Principle of GCUA Hand II

When a robot hand has a lower number of actuators than DOFs, it is called an under-actuated (UA) hand. Self-adaptive grasping is a great way to let UA hands achieve humanoid grasping. An example of self-adaptive UA hand is TH-3 hand designed by Tsinghua University^[12], each finger of TH-3 hand can use only an actuator to drive 2~3 DOFs. When the hand wants to grasp an object, actuators drive MP joints to rotate forward, PIP joints and DIP joints cannot rotate until proximal phalanges and middle phalanges are blocked by the object. In this way, the hand can grasp different objects with under-actuated function.

Another possible way is to design specific mechanisms so that joints can bend or flex in designed order. For instance, a multi-function mechanical hand with shape adaptation which was designed by G. Guo, X. Qian, and A. Gruver^[13], is based on linkage and gear transmission. With the gear transmission, PIP joints and DIP joints of the hand must rotate synchronously with a fixed proportion. In this way, the hand can use fewer motors to grasp things than a dexterous hand, however, it feels hard to meet the requirements of various humanoid movements.

GCUA Hand II uses gesture-changeable under-actuated (GCUA) function to achieve humanoid grasping and manipulations. As is shown in Fig.1, the GCUA function includes two main motions: under-actuated (UA) motion and pre-bending (PB) motion.

With UA motion, the hand can grasp different objects self-adaptively. In fact, self-adaptive grasping function which makes robot hands lower the dependence on sensor and control system, therefore, GCUA Hand II is easy to control than dexterous hands whose DOFs are also driven actively by actuators. Moreover, the hand can change its initial gesture with PB motion, which makes the hand feel easy to achieve various humanoid poses. With the combination of UA motion and PB motion, the hand can grasp objects and manipulate more dexterously and stably.

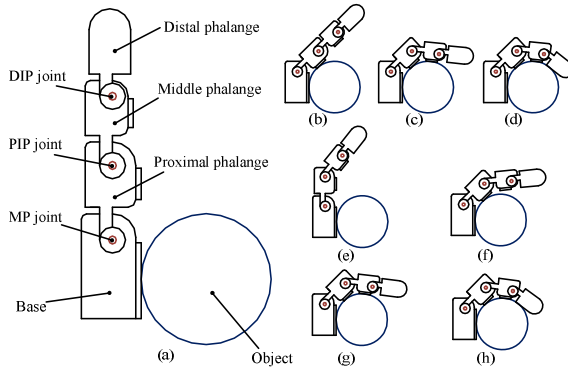


Fig. 1. UA motion and PB motion of GCUA Hand II fingers. a) Initial gesture (keep straight); b) MP joint rotates until proximal phalange touches the object; c) PIP joint rotates until middle phalange touches the object; d) DIP joint rotates until distal phalange touches the object; e) PIP joint rotates to change the finger's initial gesture; a,b,c,d) UA motion; a,e) PB motion; f-h) UA motion with the changed initial gesture.

3 Design of GCUA Hand II

As shown in Fig.2, the GCUA Hand II has 5 fingers and 14 DOFs, All of whose fingers are fixed in the palm. The sizes of the fingers are similar with people's hands: 60mm thumb, 87.5mm forefinger, 90.5mm middle finger, 84.5mm ring finger, and 75.5mm little finger, so that the GCUA Hand II can perform power grasping and some other manipulations like human beings. GCUA Hand II is composed of three modules, each module is easy to designed and maintained.

GCUA Hand II has four fingers: index finger, middle finger, ring finger and little finger. Fig. 3 and Fig. 4 show the structure of finger module.

MP joint, PIP joint, DIP joint are located in base, proximal phalange and middle phalange respectively. UA transmission and PB transmission which are both located in base use 3 tendons to achieve UA motion and PB motion. Proximal phalange is fixed with MP joint, middle phalange is fixed with PIP joint, and distal phalange is fixed with DIP joint. 1st return spring combines middle phalange and distal phalange with its two ends, similarly 2nd return spring combines proximal phalange and middle phalange with its two ends. All the joints of the finger module can bend and flex flexibly with three tendons: under-actuated (UA) tendon, restrictive (RS) tendon and

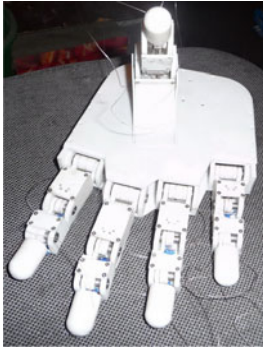


Fig. 2. GCUA Hand II

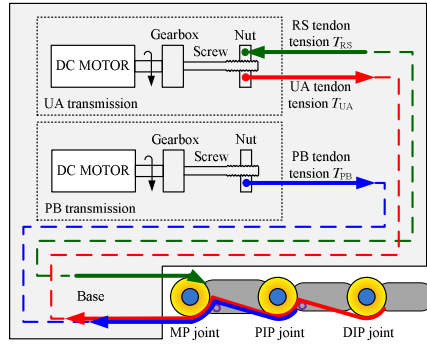


Fig. 3. Conceptual sketch map of UA motion and PB motion of the finger module

pre-bending (PB) tendon. Assembly methods of UA tendon, RS tendon, and PB tendon are shown in Fig. 4.

As is shown in Fig. 3, UA motion proceeds in this way: 1st motor rotates forward, UA transmission pulls UA tendon and RS tendon to move down. Since the wrapping directions of these two tendons are different, UA tendon will tension, simultaneously RS tendon will relax; In this case, UA tendon drives distal phalange to rotate around distal joint. With the constraint of 1st return spring and 2nd return spring, 1st middle phalange, 2nd middle phalange and distal phalange rotate around proximal joint together as a rigid body. When 1st middle phalange is blocked by objects, 2nd middle phalange and distal phalange will rotate around middle joint together, simultaneously 2nd return spring will extend; similarly, when 2nd middle phalange is blocked by objects, distal phalange will rotate around distal joint, therefore 1st return spring will extend. In this way, the finger can grasp objects self-adaptively.

As is shown in Fig.3, PB motion proceeds like this: when 2nd motor rotates forward, PB transmission pulls PB tendon to change the finger's initial gesture, since RS tendon prevents 1st middle phalange from bending and 1st return spring makes the top two phalanges become a rigid body, 2nd middle phalange and distal phalange will rotate around middle joint together, so that the finger can change its initial gesture and then grasp things with UA motion.

As is shown in Fig.5, GCUA Hand II has a thumb. The thumb module has two actuators to drive 2 DOFs. MP joint and DIP joint are located in base, proximal phalange respectively. UA transmission and PB transmission are both located in base. Proximal phalange is fixed with MP joint, and distal phalange is fixed with DIP joint. Return spring combines proximal phalange and distal phalange with its two ends.

The structure and action principle of thumb module is similar to finger module's, which reduce the difficulty to design and assemble.

GCUA Hand II has five motor driver boards. As it is shown in Fig. 6, each board has a length: 40.5mm and a width: 30.0mm. With a L293D driver IC as the center of it, each driver board can be controlled by PWM signals and drive two DC motors to run towards different directions with various rotate speeds.

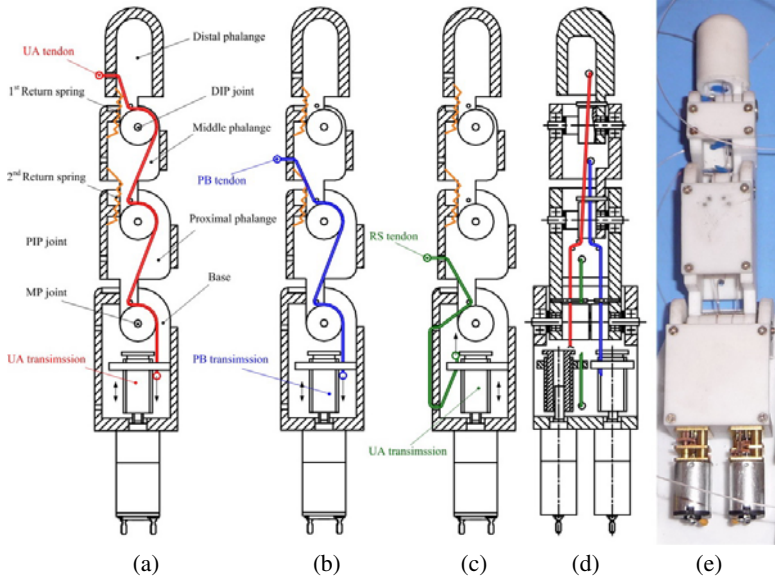


Fig. 4. Finger module. a) Assembly method of UA tendon; b) Assembly method of PB tendon; c) Assembly method of RS tendon; d) Front cutaway view; e) Finger module.

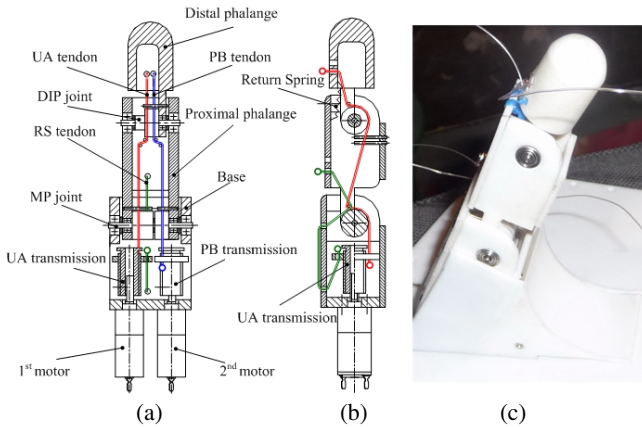


Fig. 5. Thumb module. a) Front cutaway view; b) Side cutaway view; c) Thumb module.

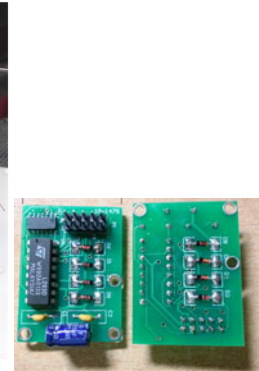


Fig. 6. Motor driver board

4 Humanoid Robot Upper Limb System

As is shown in Fig. 7, the humanoid robot upper limb system has two 3-DOF robot arms and two 14-DOF GCUA Hand II. The length of each arm is 436mm with a 206mm big arm and a 230mm forearm. The upper limb system can touch any point in a

large space exactly with 3-DOF arms and do humanoid movements dexterously with GCUA Hand II.

4.1 3-Joint Robot Arm

The arm has two parts: big arm and forearm, which is combined by 3 joints: 1st shoulder joint, 2nd shoulder joint and elbow joint. Each joint has the similar structure, which lowers the difficulty of design and the cost of manufacture. The arm is actuated by three stepper motors which can make its three joints rotate dexterously. Fig. 8(a) shows the design of each joint. Each joint rotates around a hollow shaft, which makes it feel easy to put wires through the whole arm. In fact, the design of the hollow shaft makes the whole arm move stably without impeding of wires. According to spatial analysis, with the motion of 3 joints, the terminal of the upper limb system can touch a spherical shell whose internal diameter is 146mm, and external diameter is 970mm.

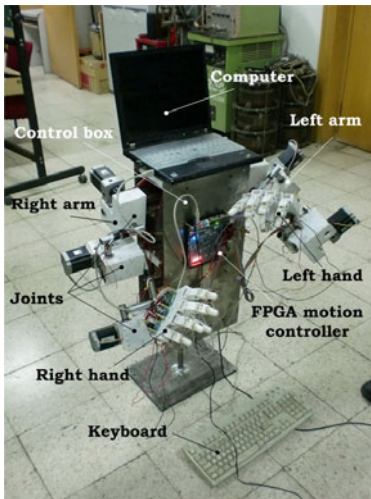


Fig. 7. Structure of the humanoid robot upper limb system with GCUA Hand II

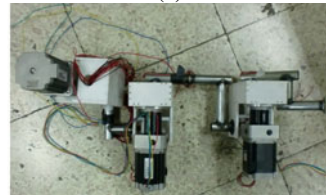
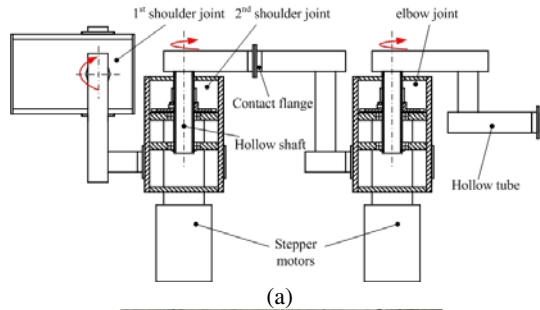


Fig. 8. Structure of 3-joint robot arm. a) Front cutaway view; b) 3-joint robot arm.

4.2 Control System

The control system includes four parts: computer, motion controller based on FPGA, driver module, and user module. Driver module consists of DC motor driver boards and stepper motor drivers, and user module consists of 3-joint robot arm and GCUA Hand II. Using VHDL to program, the computer can communicate with the motion controller through USB bus and lead the motion controller to make designed PWM signals in specific I/O port. PWM signals can control user module to achieve its function through driver module. Fig.9 shows the control diagram of GCUA humanoid robot upper limb system. With the design of robotic kinematics on the upper limb

system, the control system can control the upper limb system to achieve various humanoid manipulations.

4.3 Spatial Motion Program

Using C++ language, a spatial motion program is developed to help researchers to design specific space motions for the humanoid robot upper limb system. The spatial motion program can save the given rectangular coordinates of points. Considering different mechanical data, the program can transform the given rectangular coordinates to joint coordinates, and then give researchers the number of pulses which is needed to be given into each stepper motor driver.

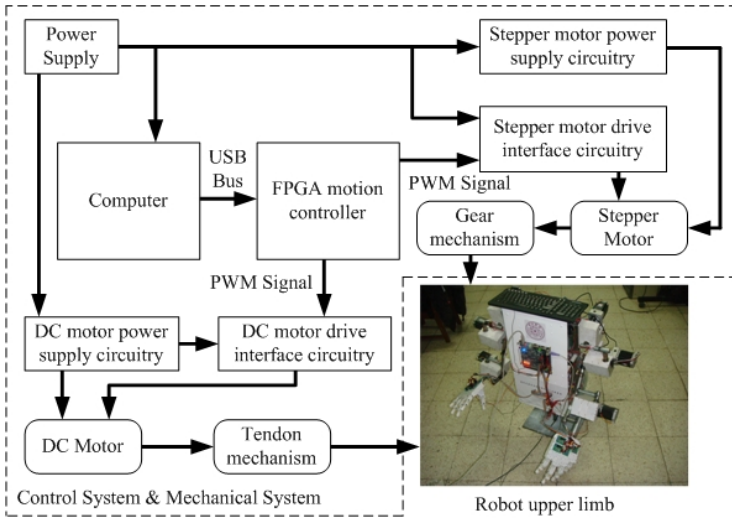


Fig. 9. Overall control diagram of the humanoid robot upper limb system

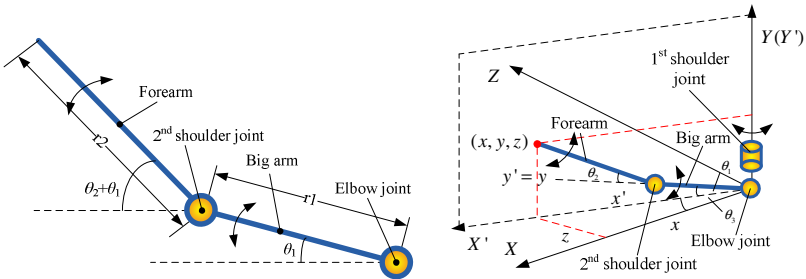


Fig. 10. Sketch map of the arm with 2 joints Fig. 11. Sketch map of the arm with 3 joints

Firstly, only consider the spatial motion of the robot upper limb on a two-dimensional plane, which is shown in Fig.10. Considering the geometrical relationship, the following equations can be obtained,

$$x = r_1 \cos \theta_1 + r_2 \cos(\theta_1 + \theta_2). \quad (1)$$

$$y = r_1 \sin \theta_1 + r_2 \sin(\theta_1 + \theta_2). \quad (2)$$

Combining eq. (1) and eq. (2), the following equations can be obtained,

$$\theta_2 = \cos^{-1} \frac{y^2 + x^2 - r_1^2 - r_2^2}{2r_1 r_2}. \quad (3)$$

$$\begin{bmatrix} r_1 + r_2 \cos \theta_2 & r_2 \sin \theta_2 \\ -r_2 \sin \theta_2 & r_1 + r_2 \cos \theta_2 \end{bmatrix} \begin{bmatrix} \sin \theta_1 \\ \cos \theta_1 \end{bmatrix} = \begin{bmatrix} y \\ x \end{bmatrix}. \quad (4)$$

Considering eq. (4), θ_2 can be obtained as follows,

$$\theta_1 = \arccos \frac{(r_1 + r_2 \cos \theta_2)x + r_2 \sin \theta_2 y}{(r_1 + r_2 \cos \theta_2)^2 + r_2^2 \sin^2 \theta_2}. \quad (5)$$

Combining eq. (3) and eq. (5), the rectangular coordinates of points can be transformed to joint coordinates. After that, consider the spatial motion of the robot upper limb on a three-dimensional space, which is shown in Fig.11. Considering geometrical relationship, the following equation can be obtained,

$$\theta_3 = \arctan(z / x). \quad (6)$$

$$x' = x / \cos \theta_3. \quad (7)$$

$$y' = y. \quad (8)$$

Combining eq. (3), (5), (7) and (8), θ_1 and θ_2 can be obtained as follows,

$$\theta_1 = \arccos \frac{(r_1 + r_2 \cos \theta_2)x' + r_2 \sin \theta_2 y'}{(r_1 + r_2 \cos \theta_2)^2 + r_2^2 \sin^2 \theta_2}. \quad (9)$$

$$\theta_2 = \cos^{-1} \frac{(y')^2 + (x')^2 - r_1^2 - r_2^2}{2r_1 r_2}. \quad (10)$$

Using eq. (6), (9) and (10), the motion program can transform rectangular coordinates of points to joint coordinates easily and exactly. After that, with the parameters of stepper motor drivers, the number of pulses which is needed to be given into each stepper motor driver can be solved out.

5 Grasping and Motion Experiments

Fig. 12 shows some grasping experiments of GCUA Hand II. The hand can grasp different objects self-adaptively with UA motion, simultaneously the cooperation of UA motion and PB motion enables the hand to do some simple operation like pressing buttons, holding a pen, and so on. As is shown in Fig. 13, the humanoid robot upper limb system can grasp a baseball stably with a nice human-like motion.

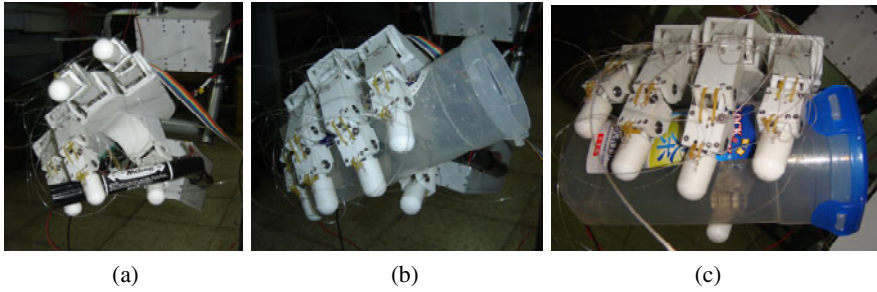


Fig. 12. Some humanoid grasping movements of GCUA Hand II. a) Hold a pen; b) Grasp a cup (cylinder); c) Grasp a cup (cube).

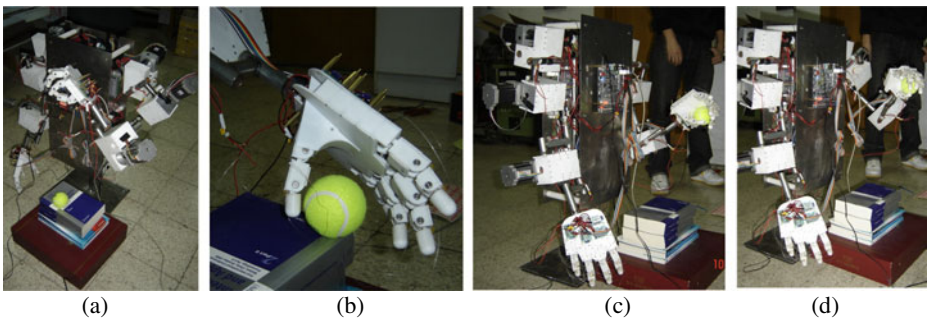


Fig. 13. The humanoid robot upper limb system grasps a baseball

6 Conclusion

GCUA function is presented which consists of two motions: UA motion and PB motion. With GCUA function, GCUA Hand II is designed which can change its initial gesture with PB motion and grasp objects self-adaptively with UA motion. The cooperation of UA motion and PB motion enables the hand to achieve various humanoid manipulations stably and dexterously. With GCUA Hand II, a dexterous humanoid robotic upper limb system is developed, which can achieve many movements and operations of human beings. Moreover, the designs of GCUA upper limb control system and spatial motion program are given. In the field of rehabilitation engineering, this system can be used to help disabled people to achieve the function of their upper limb, moreover it can also be used in many other fields like robot engineering, biological engineering, or even social services.

Acknowledgements

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Improving Positioning Accuracy of Robotic Systems by Using Environmental Support Constraints – A New Bionic Approach

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Abstract. In state of the art robotics, high positioning accuracy is achieved by using solid and stiff components as well as powerful drives. But in the field of social robotics, for example humanoid robots, it is often not possible using this approach due to special boundary conditions like design-space, weight-limitations, power-storage and many more. By contrast human beings are able to achieve remarkable high positioning accuracy despite of low mass, low power consumption and relatively simple mechanics. One approach to obtain this accuracy is to temporarily create additional supporting structures by interacting with the direct environment, for example supporting the heel of the hand on a table for writing. This article deals with the essential idea of applying this method correspondingly into the field of robotics. Using different simulations the influence on stiffness and positioning accuracy is examined. It turned out that blocking of even one degree of freedom can lead to a significant improvement regarding stiffness and therefore positioning accuracy.

Keywords: Robotics, bionic, kinematics, dynamics, positioning accuracy.

1 Introduction

In the field of humanoid robots many scientist are doing research today. The mechatronic design of humanoid robots is fundamentally different from that of industrial robots. For engineers this development area presents new challenges in mechanic design but also in all other involved domains. Compared to industrial robots – for which high velocities, mechanical rigidity, and precision (including repeating accuracy) are primary requirements – the key aspects are humanlike motions, a motion space that corresponds to that of human being and the prevention of hazards to users. In order to meet these requirements, the robot must have a humanlike appearance, motion space, and dexterity as well as a lightweight design. Additionally, its kinematics should be familiar to the user and its motions predictable, so as to encourage inexperienced persons to interact with the machine intuitively. Working scenarios of these robots are supporting humans in a variety of daily work in the household or to ease human's workload in nursing. A typical task is cooperative work of robots and

humans e.g. in the kitchen. For instance robots can support humans in bringing different items like dishes, food, or in putting dirty dishes into the dishwasher. Such tasks require sophisticated skills in cognition and object manipulation.

The collaborative research centre 588 “Humanoid Robots – learning and cooperating multi-modal robots” was established by the “Deutsche Forschungsgemeinschaft” (DFG) in Karlsruhe in May 2001. In this project, scientists from different academic fields develop concepts, methods, and concrete mechatronic components for humanoid robots called ARMAR (see Fig. 1) that can share their working space with humans. The long-term target is the interactive work of robots and humans to jointly accomplish specified tasks like helping in the kitchen.[1, 2]

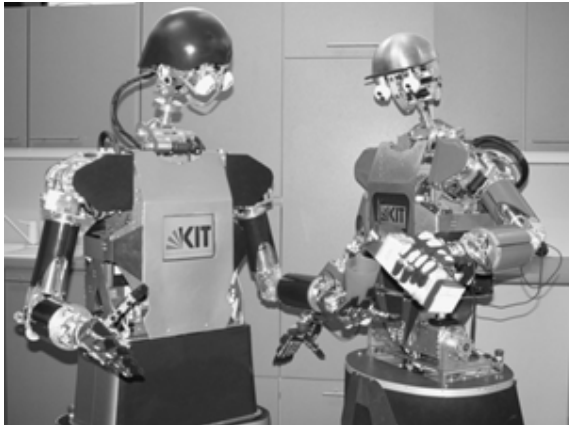


Fig. 1. Humanoid robots ARMAR IIIa / IIIb of collaborative research centre 588

In nursing robots are often used to help people getting up from bed and to sit down into a wheelchair or to walk to the bathroom [3, 4]. Communication between robots and humans should be possible in different ways, including speech, touch, and gestures, thus allowing humans to interact with the robots easily and intuitively. As a result a strict safety management is required to prevent injuries caused by the robot.

2 Motivation

For nearly all kinds of robotic systems like industrial, humanoid or service robots main requirements are high positioning and repeating accuracy during operation.

One commonly used method, especially in the development of industrial robots a structure which is as stiff as possible is realized using solid and therefore heavy components. Although these structures are optimized by means of Computer Aided Engineering (CAE) they are still heavy. Additionally in the drive chains adequate, expensive joints and gears are used which have a minimum backlash. Popular gears in the field of robotics are e.g. cyclo drive gears and precision strain wave gearing components (harmonic drive gears). They have low backlash and a high transmission ratio compared to ordinary gears like spur or planetary gears. A negative aspect of those gears is their price.

The rigidity of a structure depends on the material parameters and the geometry. The majority of industrial robots make use of solid structures to increase stiffness and therefore positioning accuracy. These heavy structures require powerful actuator and a well-engineered motor control, which both lead to high costs in components.

In some fields of robotics, for example humanoid robotics respectively social robotics, increasing of stiffness by means of solid structures is not reasonable. Those robots are designed to move autonomously; therefore low energy consumption and safety is more important than stiffness. Designers have to balance long battery life due to low mass design against stiffness due to a heavy construction. Additionally the state of technology of actuators is still not comparable with the human muscles by means of “power to weight” - and “power to size” - ratio. Another disadvantage of solid construction is that heavy robots can be hazardous to a human due to the high impact energy in case of an accident.

Nowadays, Computer Aided Engineering is widely used to minimize the weight of components while providing the required stiffness. Methods like Finite Element Method (FEM) to improve stiffness and weight of a robot have become an integral part of modern robot development [1, 2]. Despite the well-known static optimization of a structure, [5] describes dynamic computer aided optimization using the example of an arm structure of the humanoid robot ARMAR. As an industrial example Kuka and DLR presented a lightweight robot which uses carbon fiber reinforced components to increase stiffness while reducing weight [6].

Another trend in industry is to intensify the co-operation of a human worker with a robotic system using sensors like tracking and posture recognition systems [7]. In this way, companies can combine the strength and speed of robotic systems with the flexibility of humans. Furthermore service robots, which share their working space with humans, are getting more and popular [8]. The downside of this new way of human-robot cooperation is that failure of tracking systems could result in a serious accident.

To sum up, present days robotic systems often have high mass and therefore need powerful actuators with a high power consumption to achieve positioning accuracy. Furthermore they are often designed using highly optimized mechanical components. In contrast to robots, human beings are able to achieve remarkable high positioning accuracy in spite of low mass, low power consumption and relatively simple mechanics. For example human actuators (muscles) are less powerful than state of the art robotic actuators in industrial robots. The “measurement” of the joint angles is less sensitive in contrast to a high resolution sensor used in a commercial industrial robot. Additionally, the tremor the muscles of a human arm produce even at a static position, e.g. while pointing with an outstretched arm, influence the positioning accuracy in a negative way. Therefore it seems appropriate to transfer the useful characteristics resp. the way humans have learned to optimally control their mechanics into the field of robotics. So far, approaches which deal with the bionic optimization of positioning and repeat accuracy of robotic systems are normally focused on the kinematics and actuation principles of humans. These systems usually consist of multiple actuators for one degree of freedom and serial and parallel spring and cushion elements. Often the actuators are not electric motors but fluidic or pneumatic muscles. Examples for bionically inspired robots are the bionic robot arm [9] or the robot “Romo” [10] which uses pneumatic actuators.

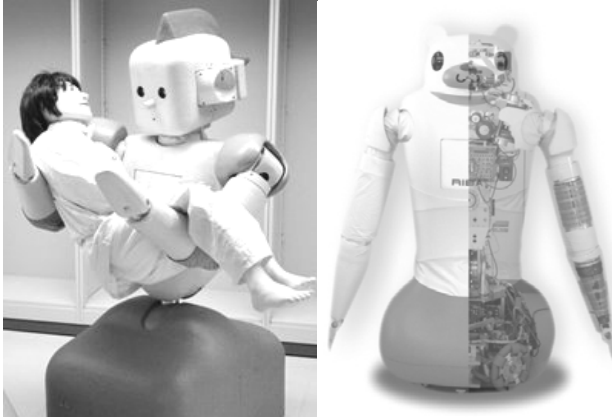


Fig. 2. RobotsRI-MAN and RIBA of NIKEN [2, 3]

In the field of social robotics, among others RI-MAN or Riba(Fig. 2)are powerful robotsbuilt to work in nursing-care facilities environment like homes or hospitals [3, 4]. RIBA for example is able to carrya payload of 61 kg but its weight is about 180kg by a relatively short operation time of one hour (standard use). Such robots would benefit using the human inspired approach to increase their “power to weight”-ratio and “working time to weight”-ratio.

3 Approach

To increase the positioning accuracy a new approach was developed at the IPEK - Institute of Product Engineering. The idea does not focus on actuators or component optimization but on the optimal operation of the already existing configuration. This approach is to temporarily create additional supporting structures with the environment like humans do in daily life situations. The goal is to increase the positioning accuracy of a kinematic chain, for example the serial kinematics of a robot arm, without adding new and complicated components or extensive control strategies.

A general approach for dealing with physical contacts to the environment based on a snake like robot is presented in [11]. In humanoid robotics amethod of interacting with the surroundingwas successfully appliedin [12]. The intentional use of the environmentto improve positioning accuracy and stiffness has not been analyzed so far.

A commonly used human method is to prop down the heel of the hand or the forearm while drawing or writing (see Fig. 3). By doing so, an additional constraint for the movements is created. This changes the distribution of forces (especially the lever arm) and the loading of extremities, joints and muscles. One simple experiment can be imagined: signing a letter with and without propping down the heel. Differences in the smoothness (accuracy in the plane of the table) but also in the pressure of the pen (accuracy perpendicular to the table), are to be expected.To calculate the equilibrium of forces, the spot of propping up can be assumed as a new mount. This leads to new constraints for the differential equations; a challenge that also existsin human-robot [13].It also results in a new kinematic structure (open chain to a restricted open chain

configuration), which was briefly discussed in [14]. Depending on the method of connection and locked degrees of freedom, deformation of the structure before the propping up spot may not affect the position of the tool center point (TCP). The power train changes and the loading of the robotic arm is reduced. The robotic arm gets insusceptible to disturbing forces and torques.

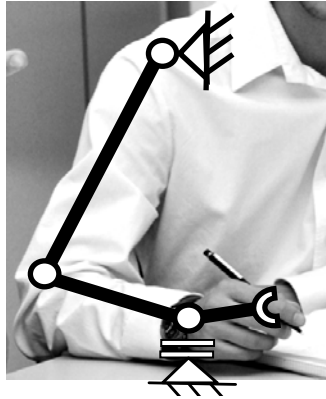


Fig. 3. Photograph of hand while writing

This allows a better position of the tool center point. Furthermore, positioning errors in the first degrees of freedom, which usually summarize up to the TCP in serial kinematics, can be cleared. These positioning errors can be e.g. backlash in the actuator and gearing, imprecise sensors or manufacturing tolerances. This approach can be used to improve positioning accuracy of the robot structure distal to the new mount. To avoid large stresses and strains, the proximal actuators were fixed after propping up. The realization of the connection with the supporting structure in technical systems like industrial or humanoid robots can be done in different ways, depending in the specific application and boundary conditions.

4 Technical Implementation

In order to realize this approach on a real robot different possibilities regarding the mechanical design of the supporting mechanism are possible. In this section, two concepts for the technical implementation of the approach are discussed. Form fitting and friction locking are chosen, because these are expected to be the mostly used types of connections in the field of humanoid respectively social robotics.

4.1 Form Fitting

By using form-fitting the effective surfaces are perpendicular to the flux of force. For instance, every object that is placed on a plane table has a form fitted connection with the table. Using form fitting to create a supporting mechanism in the environment

is one of the easiest ways to enable propping up of the robot. The complexity of a form fitting device increases with the number of blocked degrees of freedom. For example, to block one degree of freedom in one direction only one straight surface is needed. To block a larger number of degrees of freedom, a more complex device is necessary; otherwise attaching and detaching movements are getting more and more complicated.

4.2 Friction Locking

By using friction locking the effective surfaces are tangential to the direction of force. Thus, the force depends on the normal force perpendicular to the surfaces. Therefore the traction method requires an additional force control besides the position control like discussed in [15]. Additionally a slip sensor can be used in case of a changing friction coefficient during operation to increase reliability of the system. Using frictional locking as a connection method to prop up is advisable especially for humanoid robots. These types of robots are supposed to be able to move and act autonomously in many different environments, like in a kitchen or a storage room. Human beings often use gravity to create a normal force. For instance while handwriting the normal force, which is created from the mass of the arm, is sufficient to generate a friction force for adequate positioning accuracy.

Other methods e.g. using magnetic force to realize the connection between robot and support structure are not discussed in this article because they cannot reasonable be applied to the field of humanoid robots.

5 Simulation Model

To determine the effects of an additional supporting spot on the stiffness and therefore on the positioning respectively repeating accuracy of a robot arm, a simulation was implemented. In Fig. 4 the developed simplified model, a planar robotic arm with four degrees of freedom and four flexible bodies representing an arm of a humanoid robot, is depicted. At the fourth joint, the robots' arm is connected to the support spot.

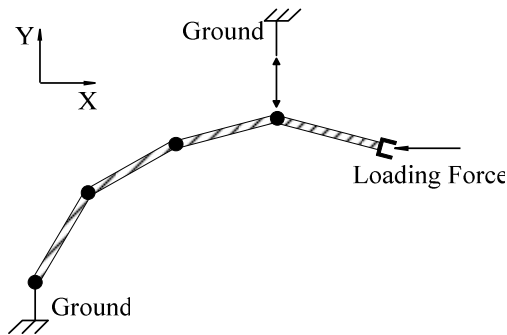


Fig. 4. Configuration of the simulated robotic arm

The model is able to represent the deflection of the links as well as torsion of the actuators and gears. In all experiments the occurring TCP-deviation is a result of the flexible joints and bodies; therefore the joint angles do not change. In order to simulate the joint deflection, all motors in the joints are modeled using springs and dampers.

5.1 Implemented Simulation Model

The library of the SimMechanics Toolbox does not provide standard blocks for flexible bodies; therefore an adequate substitute had to be found. In [16] two methods to simulate elongation respectively deformation of flexible bodies are presented. The first approach uses external software to calculate the frequency response of the rigid body. A new deformation is determined and superimposes the deformation of the solid block. The second method, which is used in this paper, discretizes a solid block into several small components that are connected using joints with springs and dampers. Thus one link n consists of a sequence of ten flexible components. The parameters for stiffness and damping were set according to the material properties of aluminum 1060.

The lumped-parameter approach is best suited to models with linear geometries, such as beams. Although this approach can be extended, bodies with a more complicated geometry are easier to model using other approaches.

5.2 Implementation of Supporting Spot

Blocking of a DOF respectively implementation of a supporting spot is realized by using a method described in [17]. The technique is based on a switch that models a spring and a damper connected to an additional linear joint. These parts have no influence until a definite position is reached. Thus the joint gets affected by a force depending on position and speed and therefore can be used as a support mechanism.

5.3 Simulations

In different experiments, the position of the TCP, the spot of propping up and the amplitude of the propping up spot have been determined. During the experiments magnitude and direction of the applied perturbation force on the TCP were systematically varied. Also the locked degrees of freedom at the supporting spot were varied in the same way. For each load case, four different experiments have been conducted: without any locking, with propping up in positive y -direction, in negative y -direction and a simulation with both directions locked. The movement of the additional joint, the spot of propping up and the TCP have also been determined. Below two exemplary results of different simulations are presented in order to show the validity of the implemented simulations. These experiments were conducted using a five second simulation with a force applied in negative x -direction between $t = 1$ and $t = 3$. The first experiment was performed without any support structure. In Fig. 5 the displacement of the TCP in x - and y -coordinates can be seen. The deviation of the TCP is 0.35 m in x - respectively 0.1 m in y -direction.

The second experiment was conducted using an additional supporting device, positive and negative y -direction blocked. In Fig. 6 the displacement of the TCP in the locked experiment can be seen.

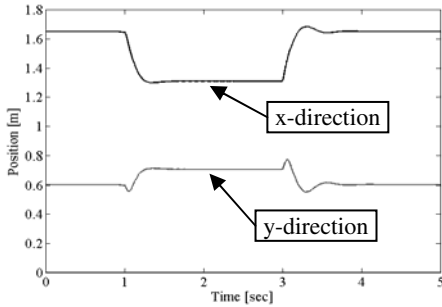


Fig. 5. Deviation of TCP without additional support (no blocking)

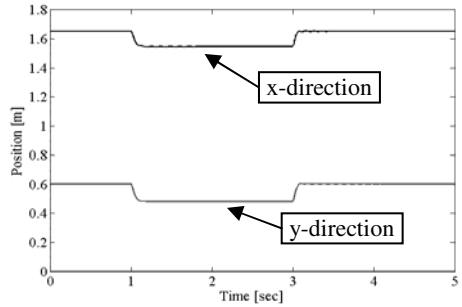


Fig. 6. Deviation of TCP with support (blocking in pos. and neg. y-direction)

Because of the applied force, the tool center point altered its x- and y-position significantly less than without an additional locking. The improvement of the positioning accuracy between a not supported and a supported robotic arm can be seen easily. The displacement of the TCP is reduced by about 0.25 m in x-direction. In contrast to the displacement without any locking, it is an improvement of >40 %. Because of the direction of the applied force the displacement in the y-direction stays more or less unchanged. In all simulations the experiments showed a significant improvement of the positioning accuracy while using locked respectively supported degrees of freedom.

5.4 Results of Simulation

The simulation showed that propping up can increase stiffness and therefore positioning accuracy of a robot arm. A complete lock in all directions enhances accuracy independently from the orientation of the loading force. The influence on the accuracy improvement of this approach also strongly depends on the joint configurations and the position of the supporting spot. A drawback of the used model is that the arrester is elastic like it would be in reality. Thus unwanted oscillations are generated. As the simulation model aims to record positions in high accuracy, the spring stiffness and damping coefficients and penetration depth of the arrester have to be chosen with care. Nevertheless, the simulation clearly shows that in increased positioning accuracy gained by the supporting method is possible. In the following some application issues of this approach on humanoid robots are discussed.

6 Humanoid Robots

In future, humanoid robots are supposed to take over more and more tasks like house-keeping or supporting elderly persons in the household e.g. in the kitchen [18]. Today in humanoid robotics lightweight components are used in order to increase the level of autonomy from stationary power supply and to limit consequences of hazard incidents. Thus, the integration of the presented method to increase positioning accuracy could be

an important way to improve functionality of such systems. Due to the importance of a humanlike appearance, only friction based locking mechanisms are preferable.

As typical scenarios for the application of the presented approach, nearly all human activities which include the use of additional support structures seem to be appropriate, like writing or precise handling tasks like putting a key in a keyhole etc.

In these scenarios two major challenges can be identified: At first, suitable spots for propping up have to be identified depending on the planned task and the available environmental conditions. This includes the decision which component of the robot should be used for propping up: the elbow, a complete forearm or the heel of the hand only. Second, after defining an adequate spot for propping up, it has to be guaranteed that this connection works properly during the performed task. Due to a potentially changing friction coefficient, for example due to spilled milk or water, this will require adequate slip sensors. Also the influence of the additional constraints due to the added support on the kinematics of the system has to be studied in detail.

For more complex tasks also the possibility of reducing vibrations of the upper body or even maintaining stability of the whole robot by holding on a wall or handrail has to be investigated. This issue can become important when supporting elderly personse.g. on a staircase in order to increase safety.

7 Conclusion and Forecast

A new bionically inspired approach to increase positioning accuracy of humanoid robots was presented. After the presentation of the underlying idea, different simulations representing a simplified humanoid robot arm with four DOFs were conducted. The results of the simulations proved that this approach is able to increase positioning accuracy of humanoid robots, but can also be applied to other kinds of robots like industrial or snake-arm robots. On the one hand functionality can be increased by taking advantage of a higher accuracy on the other hand the same accuracy can be achieved by using less accurate and therefore cheaper components. For social robots in the field of physically supporting elderly people propping up can also increase the safety due to the increased stability of the system. Drawbacks of propping up are a reduction of the maximum force and working space which limits the application in some scenarios.

The next steps in this work will be to set up specific scenarios in the household context of the humanoid robot ARMAR. Here possible scenarios can be fine manipulation tasks like writing (e.g. a shopping list) or precise pick-and-place jobs. The successful application of this approach strongly depends on the development of adequate algorithms for the detection of suitable propping up spots and the determination of the optimal joint for propping. Both will be supported by using a new dynamic simulation model and the real robot arm of the next generation of ARMAR.

Acknowledgments

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Nonlinear Control of a Robot Manipulator with Time-Varying Uncertainties

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Abstract. In this paper, two nonlinear control methods including adaptive learning control and adaptive robust control are designed for a robotic manipulator with time-varying uncertainties. We first present an adaptive learning control by incorporated learning control approaches into an adaptive control system to handle periodic uncertainties with known periods. We explore Lyapunov functional method to design the controller such that the convergence of tracking errors can be ensured. If the periods of uncertainties are unknown or uncertainties are non-periodic, an adaptive robust control is further designed to guarantee that the solution trajectory is finite and arbitrarily close to the desired trajectory by choosing design parameters in the controller. The efficacy of the proposed nonlinear controllers has been demonstrated in a two-link robot manipulator.

Keywords: Adaptive learning control, adaptive robust control, robotic dynamic systems, time-varying uncertainties.

1 Introduction

A robot manipulator with uncertainties can be transformed into the form of nonlinear dynamical systems with unknown constant parameters, unknown time-varying factors and non-linear functions of system state variables. For setpoint control, the simple controllers such as the PD and PID feedback are effective in [1]. A lot of nonlinear control methods including adaptive control and robust control have been presented to handle trajectory tracking problem [5], [7], [11], [12], [13], [14] and [15].

By applying Lyapunov function, adaptive control has been widely studied to deal with the constant uncertainties in the robot model [5] and [14]. Robust control can be applied to highly non-linear and uncertain systems in [11] and [15] with the known upper bounds of uncertainties regardless they are constant, time-varying or non-linear functions of system state variables. In [6] and [8], incorporating the capability of neural networks into an adaptive control system, adaptive neural-network control has been presented to deal with non-linear uncertainties of system state variables without the knowledge of the upper bounds of uncertainties. The objective of learning control is to improve the system performance by updating the control input. In order to solve time-varying

uncertainties in a fixed finite time interval or periodic uncertainties, learning control has been designed in [3], [4] and [10].

However, in the above research related learning control [3], [4] and [10], it has assumed that the robotic systems perform the same tasks in a fixed finite time interval. In [16] despite the learning control strategy has also been extended to reject periodic disturbances, it requires the desired trajectory is repeated or periodic. In this work, firstly an adaptive learning control is presented by incorporated learning control approaches into an adaptive control system to handle periodic uncertainties with known periods. We will design a Lyapunov functional to ensure the trajectory can track the desired trajectory by using the proposed controller. Furthermore, if the periods of uncertainties are unknown or uncertainties are non-periodic, we further design an adaptive robust control by integrating of robust and adaptive control approaches. Compared with the existing robust control method in [11], [12] and [15], our proposed controller has not a requirement for the upper bounds of uncertainties. Based on the proposed control approach, the solution trajectory is finite and arbitrarily close to the desired trajectory by choosing design parameters in the controller.

The remainder of this paper is organized as follows. Section 2 gives problem formulation and preliminaries. In Section 3, we present the nonlinear control design including adaptive learning control and adaptive robust control for a robot manipulator. The simulation study in Section 4 illustrates the performance of the designed control. And we present concluding remarks in Section 5.

2 Problem Formulation and Preliminaries

Consider a robot manipulator described by:

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + \tau_d = \tau \tag{1}$$

where $q \in R^n$ is the robot joint position, $D(q) \in R^{n \times n}$ is the inertia matrix, $C(q, \dot{q}) \in R^{n \times n}$ is the Coriolos and centrifugal forces matrix, $G(q) \in R^n$ is the gravity vector, $\tau \in R^n$ is the input torques and $\tau_d \in R^n$ is unknown bounded disturbances. The following properties hold ([1] and [7]).

Property 1. The inertia matrix $D(q)$ is symmetric positive definite.

Property 2. The matrix $\dot{D}(q) - 2C(q, \dot{q})$ is skew-symmetric.

Property 3. The dynamic model as described by (1) can be linearly parameterized as follows ([14], [7] and [6]): $D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \xi(q, \dot{q}, \ddot{q})\theta$ where $\theta = (\theta_1, \dots, \theta_p)^T$ is the vector of unknown constant parameters and $\xi(\cdot) \in R^{n \times p}$ is a known regressor function.

Let $x \in R^m$ be a task space vector defined by $x = h(q)$, where $m \leq n$ and $h(\cdot) \in R^m$ is a transformation function between the joint space and task space. By considering the differential kinematics relating the two spaces, we have $\dot{x} = J(q)\dot{q}$, where $J \in R^{m \times n}$ is the Jacobian matrix from joint space to task space.

For a given desired trajectory x_d in the task space, our objective is to design a controller τ such that $q \rightarrow q_d$ and $x \rightarrow x_d$. Generally the closed loop inverse kinematics methods (CLIK) is applied to obtain the desired q_d in the joint space. We can calculate the desired joint velocity by $\dot{q}_d = J^*(\dot{x}_d - ke_t)$, where k is a positive constant and $J^* = W_1^{-1}J^T(JW_1^{-1}J^T + W_2)^{-1}$ denotes the regularized right pseudo-inverse of J weighted by the positive definite matrix W_1 and regularized by the positive definite damping matrix W_2 and $e_t = \hat{X}_t - X_t$, \hat{X}_t calculated by forward kinematics. If $W_2 = 0$, J^* is simply the weighted right pseudo-inverse of J . Furthermore, if J is a square nonsingular matrix, W_1 is the identity matrix and $W_2 = 0$, we can simply replace J^* by the standard matrix inversion J^{-1} . The damping matrix W_2 is necessary for ill-conditioned J . If choosing $W_2 = \lambda^2 I$, where $\lambda > 0$ is the damping factor and I is the identity matrix, small values of λ give accurate solutions but low robustness to the occurrence of singular and near-singular configurations. However, large values of λ result in low tracking accuracy even when a feasible and accurate solution would be possible. The damping factor establishes the relative weight between the two objectives. Methods in [9] and [2] are given to show how to adaptively select the damping factor based on some measure of closeness of the singularity at the current configuration.

Now define the filtered tracking error $\sigma_q = \dot{e}_q + \lambda e_q$ where $e_q = q_d - q$ is the tracking error and $\lambda > 0$ is a design parameter. We further have the differential equation of σ_q as follows: $\dot{\sigma}_q = \ddot{e}_q + \lambda \dot{e}_q$.

Remark 1. In the definition of σ_q , e_q can be taken as the output of a stable dynamic system with σ_q as input since $\lambda > 0$. This implies that e_q and \dot{e}_q are bounded if σ_q is bounded.

The equation of motion can be further expressed as

$$D(q)\dot{\sigma}_q + C(q, \dot{q})\sigma_q + D(q)\ddot{q}_r + C(q, \dot{q})\dot{q}_r + G(q) = \tau - \tau_d \quad (2)$$

where $\dot{q}_r = \dot{q}_d + \lambda e_q$ and $\ddot{q}_r = \ddot{q}_d + \lambda \dot{e}_q$. According to Property 3, the last three terms of the left-hand-side expression of (2) can be linearly parameterized in terms of the robot system parameters as follows:

$$D(q)\ddot{q}_r + C(q, \dot{q})\dot{q}_r + G(q) = \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\theta. \quad (3)$$

Thus we obtain the dynamic system of tracking error in the following

$$D(q)\dot{\sigma}_q + C(q, \dot{q})\sigma_q + \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\theta = \tau - \tau_d. \quad (4)$$

The following properties are used to give the convergence analysis in the adaptive learning control design [17].

Property 4. Let $\phi(t) \in R$ and $T > 0$ be a finite constant. The upper right-hand derivative of $\int_{t-T}^t \phi^2(s)ds$ is $\phi^2(t) - \phi^2(t-T)$.

Property 5. Let $\phi(t), \hat{\phi}(t), \tilde{\phi}(t), f(t) \in R$, and assume that the following relations hold $\phi(t) = \phi(t-T)$, $\tilde{\phi}(t) = \phi(t) - \hat{\phi}(t)$, $\dot{\tilde{\phi}}(t) = \dot{\hat{\phi}}(t-T) + f(t)$. Then the upper right-hand derivative of $\int_t^{t-T} \tilde{\theta}(s)ds$ is $-2\tilde{\theta}(t)f(t) - f^2(t)$.

In order to deal with the non-periodic time-varying uncertainty τ_d , we denote $S(x) = \rho_1 \arctan(\rho_2 x)$, for any variable x , where $\rho_1 > 0$ and $\rho_2 > 0$ are positive constants to be chosen by the designer. Note that if we choose the gains ρ_1 and ρ_2 such that $\frac{1}{\rho_2} \tan \frac{1}{\rho_1} \leq \delta$, then $xS(x) = x\rho_1 \arctan(\rho_2 x) \geq \begin{cases} |x| & |x| \geq \delta \\ x^2/\delta & |x| < \delta. \end{cases}$ It is easy to verify that $S(x)$ is continuous and differentiable. We have the following property in [18].

Property 6. $|x| - S(x)x \leq \delta$.

3 Nonlinear Tracking Control Design

In this section, we will present adaptive learning tracking controller and adaptive robust controller to deal with periodic and non-periodic time-varying uncertainties τ_d in the robot manipulator model (1).

3.1 Adaptive Learning Control Design

Assume that the disturbance $\tau_d = [\tau_{d1}, \dots, \tau_{dn}]$ is periodic with known periods $T_i, i = 1, \dots, n$. Design the adaptive learning control law as

$$\tau = Q\sigma_q + \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{\theta} + \hat{\tau}_d \tag{5}$$

$$\dot{\hat{\theta}} = \Gamma \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\sigma_q \tag{6}$$

$$\hat{\tau}_{di}(t) = \hat{\tau}_{di}(t - T_i) - \gamma_i \sigma_{qi}, \quad i = 1, \dots, n, \quad \hat{\tau}_{di}(t) = 0, \quad \forall t \in [-T_i, 0] \tag{7}$$

where feedback gain Q is chosen as a positive definite diagonal matrix, satisfying $Q \geq (\epsilon_1 + \epsilon_2)I$ with constant ϵ_1 and $\epsilon_2 > 0$ to be specified and $\hat{\tau}_d = [\hat{\tau}_{d1}, \dots, \hat{\tau}_{dn}]^T$. Γ is diagonal matrix with positive diagonal elements and γ_i are positive constants. Without the loss of generality, assume $T_n \geq T_{n-1} \geq \dots \geq T_1$.

The close-loop dynamics is obtained by substituting (5) into (4) to give $D(q)\dot{\sigma}_q + C(q, \dot{q})\sigma_q + \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)(\theta - \hat{\theta}) - Q\sigma_q + (\tau_d - \hat{\tau}_d) = 0$. By defining $\tilde{\theta} = \theta - \hat{\theta}$ and $\tilde{\tau}_d = \tau_d - \hat{\tau}_d = [\tilde{\tau}_{d1}, \dots, \tilde{\tau}_{dn}]^T$, the close-loop dynamics becomes

$$D(q)\dot{\sigma}_q + C(q, \dot{q})\sigma_q + \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\tilde{\theta} - Q\sigma_q + \tilde{\tau}_d = 0. \tag{8}$$

To facilitate the convergence analysis, define the following Lyapunov-Krasovskii functional with $V_1 = \frac{1}{2}\sigma_q^T D(q)\sigma_q + \frac{1}{2}\tilde{\theta}^T \Gamma^{-1}\tilde{\theta}$

$$V(t, \sigma_q, \tilde{\theta}, \tilde{\tau}_{di}) = V_1 + \begin{cases} \sum_{i=1}^n \frac{1}{2\gamma_i} \int_0^t \tilde{\tau}_{di}^2(s) ds, & t \in [0, T_1) \\ \frac{1}{2\gamma_1} \int_{t-T_1}^t \tilde{\tau}_{d1}^2(s) ds + \sum_{i=2}^n \frac{1}{2\gamma_i} \int_0^t \tilde{\tau}_{di}^2(s) ds, & t \in [T_1, T_2) \\ \vdots \\ \sum_{i=1}^n \frac{1}{2\gamma_i} \int_{t-T_i}^t \tilde{\tau}_{di}^2(s) ds. & t \in [T_n, \infty) \end{cases}$$

Theorem 1. *The control law (5) with the parametric updating law in (6) and (7) warrants the asymptotical convergence $\lim_{t \rightarrow \infty} \int_{t-T_n}^t \sigma_q^T \sigma_q ds = 0$.*

Proof. Firstly, we derive the upper right hand derivative of V for $t \in [0, T_1)$, which is $\dot{V} = \dot{V}_1 + \sum_{i=1}^n \frac{1}{2\gamma_i} \tilde{\tau}_{di}^2(t)$. Using the skew-symmetric property of matrix $\dot{D}(q) - 2C(q, \dot{q})$ in Property 2, \dot{V}_1 along (8) is calculated as

$$\begin{aligned} \dot{V}_1 &= \sigma_q^T D(q) \dot{\sigma}_q + \frac{1}{2} \sigma_q^T \dot{D}(q) \sigma_q + \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} \\ &= \sigma_q^T D(q) \dot{\sigma}_q + \sigma_q^T C(q, \dot{q}) \sigma_q - \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} \\ &= -\sigma_q^T Q \sigma_q + \sigma_q^T \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r) \tilde{\theta} - \sigma_q^T \tilde{\tau}_d - \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}}. \end{aligned}$$

Using the updating law in (6), we obtain

$$\dot{V}_1 = -\sigma_q^T Q \sigma_q - \sigma_q^T \tilde{\tau}_d. \tag{9}$$

It is known $\hat{\tau}_{di} = -\gamma_i \sigma_{qi}$ for $t \in [0, T_1)$, therefore $\tilde{\tau}_{di}^2(t) = \tau_{di}^2(t) - 2\hat{\tau}_{di}(t)\tilde{\tau}_{di}(t) - \hat{\tau}_{di}^2(t) \leq \tau_{di}^2 + 2\gamma_i \tilde{\tau}_{di}(t)\sigma_{qi}$. In the sequel, the upper right hand derivation of V for $t \in [0, T_1)$ is $\dot{V} = -\sigma_q^T Q \sigma_q + \sum_{i=1}^n \frac{1}{2\gamma_i} \tau_{di}^2$. Note that $\tau_{di}, i = 1, \dots, n$ are periodic, thus are bounded. The finiteness of \dot{V} warrants the finiteness of V in a finite time interval $[0, T_1)$.

According to Property 4 and (9), \dot{V} for $t \in [T_1, T_2)$ is

$$\begin{aligned} \dot{V} &= \dot{V}_1 + \sum_{i=2}^n \frac{1}{2\gamma_i} \tilde{\tau}_{di}^2(t) + \frac{1}{2\gamma_1} (\tilde{\tau}_{d1}^2(t) - \tilde{\tau}_{d1}^2(t - T_1)) \\ &= -\sigma_q^T Q \sigma_q - \sigma_q^T \tilde{\tau}_d + \sum_{i=2}^n \frac{1}{2\gamma_i} \tilde{\tau}_{di}^2(t) + \frac{1}{2\gamma_1} (\tilde{\tau}_{d1}^2(t) - \tilde{\tau}_{d1}^2(t - T_1)). \end{aligned} \tag{10}$$

For $t \in [T_1, T_2)$, we still have $\tilde{\tau}_{di}^2(t) \leq \tau_{di}^2 + 2\gamma_i \tilde{\tau}_{di}(t)\sigma_{qi}$ for $i \geq 2$. According to Property 5 and the updating law in (7), $\tilde{\tau}_{d1}^2(t) - \tilde{\tau}_{d1}^2(t - T_1) = 2\gamma_1 \tilde{\tau}_{d1} \sigma_{q1} - \gamma_1 \sigma_{q1}^2$. Thus \dot{V} for $t \in [T_1, T_2)$ is $\dot{V} = -\sigma_q^T Q \sigma_q - \frac{1}{2} \sigma_{q1}^2 + \sum_{i=1}^n \frac{1}{2\gamma_i} \tau_{di}^2$. Obviously \dot{V} is finite for $t \in [T_1, T_2)$ because of the finiteness of the periodic function $\tau_{di}(t)$. Thus V is bounded in $[T_1, T_2)$.

Similar as the above procedure, we can get \dot{V} for $t \in [T_{n-1}, T_n)$ as follows $\dot{V} = -\sigma_q^T Q \sigma_q - \frac{1}{2} \sum_{i=1}^{n-1} \sigma_{qi}^2 + \frac{1}{2\gamma_n} \tau_{dn}^2$. This also implies that V is bounded for t in a finite time interval $[T_{n-1}, T_n)$.

Now we calculate \dot{V} for $t \in [T_\infty, \infty)$. According to Property 4, $\dot{V} = \dot{V}_1 + \sum_{i=1}^n \frac{1}{2\gamma_i} (\tilde{\tau}_{di}^2(t) - \tilde{\tau}_{di}^2(t - T_i))$. Moreover we can get $\tilde{\tau}_{di}^2(t) - \tilde{\tau}_{di}^2(t - T_i) = 2\gamma_i \tilde{\tau}_{di} \sigma_{qi} - \gamma_i \sigma_{qi}^2$ from Property 5 and the parametric updating law (7). Considering \dot{V}_1 in (9), the following equation can be obtained

$$\dot{V} = -\sigma_q^T Q \sigma_q - \frac{1}{2} \sum_{i=1}^n \sigma_{qi}^2 \leq -\sigma_q^T Q \sigma_q. \tag{11}$$

Finally we derive the convergence property $\lim_{t \rightarrow \infty} \int_{t-T_n}^t \sigma_q^2(\tau) d\tau = 0$. Suppose that $\lim_{t \rightarrow \infty} \int_{t-T_n}^t \sigma_q^T(\tau) \sigma_q(\tau) d\tau \neq 0$. Then there exist an $\epsilon > 0$, a $t_0 > T_n$ and a sequence $t_i \rightarrow \infty$ with $i = 1, 2, \dots$ and $t_{i+1} \geq t_i + T_n$ such that $\int_{t_i}^{t_i+T_n} \sigma_q^2(\tau) d\tau > \epsilon$ when $t_i > t_0$. Thus from (11), we have for $t > T_n$, $\lim_{t \rightarrow \infty} V(t) \leq V(T_n) - \lim_{t \rightarrow \infty} \sum_{j=1}^i \int_{t_j-T_n}^{t_j} \sigma_q^T Q \sigma_q d\tau$. Since $V(T_n)$ is finite, the above equation implies $\lim_{t \rightarrow \infty} V(t) \rightarrow -\infty$. Thus this will make a contradiction to the property that $\lim_{t \rightarrow \infty} V(t)$ is positive.

This complete the proof.

Remark 2. From theoretical analysis, it is only required that $Q = \text{diag}\{q_{ii}\}$ and $\Gamma = \text{diag}\{\gamma_{ii}\}$ are positive diagonal matrices and $\gamma_{ii} > 0$ to get convergence performance. Similar to PID control, different values of q_{ii} , γ_{ii} and γ_i will affect the convergence speed. If these values are too small, the system needs a long time to reach the stable state. However, if they are too large, the control signal may be too large to realize in practice. The reader can find a suitable value to get a satisfied performance by tuning values of them.

3.2 Adaptive Robust Control Design

The requirement of the above adaptive learning control method is the known periods of periodic uncertainties. Now we design adaptive robust control method to deal with more general time-varying uncertainties. Assume disturbances τ_d be bounded with unknown bounds. Denote $\beta_\tau = [\beta_{\tau 1}, \dots, \beta_{\tau i}, \dots, \beta_{\tau n}]^T$, where $\beta_{\tau i}$ is the bound of τ_{di} . Consider the error dynamics (4), the adaptive robust control law is

$$\tau = Q\sigma_q + \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\hat{\theta} + S(\hat{\beta}_\tau^T \sigma_q)\hat{\beta}_\tau \tag{12}$$

$$\dot{\hat{\theta}} = \Gamma \xi^T(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\sigma_q \tag{13}$$

$$\dot{\hat{\beta}}_\tau = \bar{\sigma}_q - \Lambda \hat{\beta}_\tau \tag{14}$$

where feedback gain Q has the same definition as (5). $\bar{\sigma}_q = [|\sigma_{q1}|, \dots, |\sigma_{qn}|]^T$, Γ and Λ are diagonal matrices with positive diagonal elements γ_{ii} and λ_{ii} .

The close-loop dynamics is obtained by substituting (12) into (4) to yield

$$D(q)\dot{\sigma}_q + C(q, \dot{q})\sigma_q + \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r)(\theta - \hat{\theta}) - Q\sigma_q + (\tau_d - S(\hat{\beta}_\tau^T \sigma_q)\hat{\beta}_\tau) = 0. \tag{15}$$

Theorem 2. *The control law (12) with the parametric updating law in (13) and (14) guarantees the finiteness of tracking error σ_q in the large and the bound of σ_q is $\sigma_q^T Q \sigma_q \leq \frac{1}{2} \|\Lambda\| \cdot \|\beta_\tau\|^2 + \delta + \epsilon$.*

Proof. To facilitate the convergence analysis, define the following Lyapunov function $V(t, \sigma_q, \tilde{\theta}, \tilde{\tau}_d) = \frac{1}{2} \sigma_q^T D(q) \sigma_q + \frac{1}{2} \tilde{\theta}^T \Gamma^{-1} \tilde{\theta} + \frac{1}{2} (\beta_\tau - \hat{\beta}_\tau)^T (\beta_\tau - \hat{\beta}_\tau)$. Now derive the derivative of V for t , which is

$$\dot{V} = \sigma_q^T D(q) \dot{\sigma}_q + \frac{1}{2} \sigma_q^T \dot{D}(q) \sigma_q + \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} - (\beta_\tau - \hat{\beta}_\tau)^T \dot{\tilde{\beta}}_\tau. \tag{16}$$

By appealing to the skew-symmetric property of matrix $\dot{D}(q) - 2C(q, \dot{q})$ in Property 2, \dot{V} along (15) is

$$\begin{aligned}
\dot{V} &= \sigma_q^T D(q) \dot{\sigma}_q + \sigma_q^T C(q, \dot{q}) \sigma_q - \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} - (\beta_\tau - \hat{\beta}_\tau)^T \dot{\hat{\beta}}_\tau \\
&= \sigma_q^T (\xi(q, \dot{q}), \dot{q}_r, \ddot{q}_r) \tilde{\theta} - Q \sigma_q + (\tau_d - S(\hat{\beta}_\tau^T \sigma_q) \hat{\beta}_\tau) - \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} - (\beta_\tau - \hat{\beta}_\tau)^T \dot{\hat{\beta}}_\tau \\
&= -\sigma_q^T Q \sigma_q + \sigma_q^T \xi(q, \dot{q}, \dot{q}_r, \ddot{q}_r) \tilde{\theta} - \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} + \tau_d^T \sigma_q \\
&\quad - S(\hat{\beta}_\tau^T \sigma_q) \hat{\beta}_\tau^T \sigma_q - (\beta_\tau - \hat{\beta}_\tau)^T \dot{\hat{\beta}}_\tau. \tag{17}
\end{aligned}$$

Substituting the updating law in (13) into the above equation yields

$$\begin{aligned}
\dot{V} &= -\sigma_q^T Q \sigma_q + \tau_d^T \sigma_q - S(\hat{\beta}_\tau^T \sigma_q) \hat{\beta}_\tau^T \sigma_q - (\beta_\tau - \hat{\beta}_\tau)^T \dot{\hat{\beta}}_\tau \\
&\leq -\sigma_q^T Q \sigma_q + \beta_\tau^T \bar{\sigma}_q - \hat{\beta}_\tau^T \bar{\sigma}_q + \hat{\beta}_\tau^T \bar{\sigma}_q - S(\hat{\beta}_\tau^T \sigma_q) \hat{\beta}_\tau^T \sigma_q - (\beta_\tau - \hat{\beta}_\tau)^T \dot{\hat{\beta}}_\tau \\
&= -\sigma_q^T Q \sigma_q + \hat{\beta}_\tau^T \bar{\sigma}_q - S(\hat{\beta}_\tau^T \sigma_q) \hat{\beta}_\tau^T \sigma_q + (\beta_\tau - \hat{\beta}_\tau)^T \Lambda \hat{\beta}_\tau \tag{18}
\end{aligned}$$

Considering the Property 6, we have

$$\hat{\beta}_\tau^T \bar{\sigma}_q - S(\hat{\beta}_\tau^T \sigma_q) \hat{\beta}_\tau^T \sigma_q \leq \delta. \tag{19}$$

Furthermore,

$$\begin{aligned}
(\beta_\tau - \hat{\beta}_\tau)^T \Lambda \hat{\beta}_\tau &= -(\hat{\beta}_\tau^T \Lambda \hat{\beta}_\tau - \beta_\tau^T \Lambda \hat{\beta}_\tau) \\
&\leq -\left(\frac{1}{2} \hat{\beta}_\tau^T \Lambda \hat{\beta}_\tau - \beta_\tau^T \Lambda \hat{\beta}_\tau + \frac{1}{2} \beta_\tau^T \Lambda \beta_\tau\right) + \frac{1}{2} \beta_\tau^T \Lambda \beta_\tau \\
&= -\frac{1}{2} \|\Lambda^{\frac{1}{2}} (\beta_\tau - \hat{\beta}_\tau)\|^2 + \frac{1}{2} \|\Lambda\| \cdot \|\beta_\tau\|^2. \tag{20}
\end{aligned}$$

Substituting (19) and (20) into (18), we achieve

$$\begin{aligned}
\dot{V} &= -\sigma_q^T Q \sigma_q + \delta - \frac{1}{2} \|\Lambda^{\frac{1}{2}} (\beta_\tau - \hat{\beta}_\tau)\|^2 + \frac{1}{2} \|\Lambda\| \cdot \|\beta_\tau\|^2 \\
&= -\sigma_q^T Q \sigma_q - \frac{1}{2} \|\Lambda^{\frac{1}{2}} (\beta_\tau - \hat{\beta}_\tau)\|^2 + \delta + \frac{1}{2} \|\Lambda\| \cdot \|\beta_\tau\|^2. \tag{21}
\end{aligned}$$

Thus \dot{V} is negative definite outside the compact set $M = \{\sigma_q : \sigma_q^T Q \sigma_q + \frac{1}{2} \|\Lambda^{\frac{1}{2}} (\beta_\tau - \hat{\beta}_\tau)\|^2 \leq \frac{1}{2} \|\Lambda\| \cdot \|\beta_\tau\|^2 + \delta\}$. Further define an ϵ -neighborhood of M_ϵ with $\epsilon > 0$, $M_\epsilon = \{\sigma_q : \sigma_q^T Q \sigma_q + \frac{1}{2} \|\Lambda^{\frac{1}{2}} (\beta_\tau - \hat{\beta}_\tau)\|^2 \leq \frac{1}{2} \|\Lambda\| \cdot \|\beta_\tau\|^2 + \delta + \epsilon\}$, then $\dot{V} \leq -\epsilon$. σ_q will enter the ϵ -neighborhood M_ϵ in a finite time, which implies the asymptotic convergence to the region in Theorem 2.

This completes the proof.

4 Simulation

In the simulation study, for simplicity we consider a two-link robot moving in a horizontal plane shown in Fig.1. The robot dynamics are modeled by (1) with

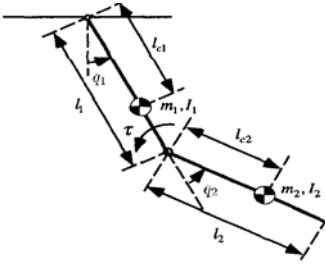


Fig. 1. The mathematical model of a two-link rigid robot arm

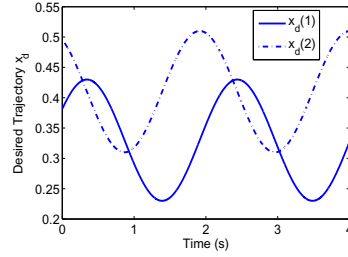


Fig. 2. The desired trajectories x_d

$$D(q) = \begin{bmatrix} \theta_1 + \theta_2 + 2\theta_3 c_2 & \theta_2 + \theta_3 c_2 \\ \theta_2 + \theta_3 c_2 & \theta_2 \end{bmatrix}, \quad C(q, \dot{q}) = \begin{bmatrix} -\theta_3 s_2 \dot{q}_2 & -\theta_3 s_2 (\dot{q}_1 + \dot{q}_2) \\ \theta_3 s_2 \dot{q}_1 & 0 \end{bmatrix},$$

$$G(q) = \begin{bmatrix} \theta_4 c_1 + \theta_5 c_{12} \\ \theta_5 c_{12} \end{bmatrix}, \quad (22)$$

where $\theta_1 = m_1 l_{c1}^2 + m_2 l_1^2 + I_1$, $\theta_2 = m_2 l_{c2}^2 + I_2$, $\theta_3 = m_2 l_1 l_{c2}$, $\theta_4 = (m_1 l_{c1} + m_2 l_1)g$, $\theta_5 = m_2 g l_{c2}$ and $s_1 = \sin(q_1)$, $s_2 = \sin(q_2)$, $c_1 = \cos(q_1)$, $c_2 = \cos(q_2)$, $s_{12} = \sin(q_1 + q_2)$, $c_{12} = \cos(q_1 + q_2)$. The pairs $\{m_1, m_2\}$, $\{I_1, I_2\}$, $\{l_1, l_2\}$ and $\{l_{c1}, l_{c2}\}$ are the masses, moments of inertia, lengths and center of gravity co-ordinates of the two robotic arm respectively.

Based on (22), we have $D(q)\ddot{q}_r + C(q, \dot{q})\dot{q}_r + G(q) = \xi(q, \dot{q}, \ddot{q}_r)\theta$ with $\theta = [\theta_1 \ \theta_2 \ \theta_3 \ \theta_4 \ \theta_5]$, $\xi(q, \dot{q}, \ddot{q}_r) = \begin{bmatrix} \xi_{11} & \xi_{12} & \xi_{13} & \xi_{14} & \xi_{15} \\ \xi_{21} & \xi_{22} & \xi_{23} & \xi_{24} & \xi_{25} \end{bmatrix}$, where $\xi_{11} = \ddot{q}_{r1}$, $\xi_{12} = \ddot{q}_{r1} + \ddot{q}_{r2}$, $\xi_{13} = 2c_2\ddot{q}_{r1} + c_2\ddot{q}_{r2} - s_2\dot{q}_2\dot{q}_{r1} - s_2(\dot{q}_1 + \dot{q}_2)\dot{q}_{r2}$, $\xi_{14} = c_1$, $\xi_{15} = c_{12}$, $\xi_{21} = 0$, $\xi_{22} = \ddot{q}_{r1} + \ddot{q}_{r2}$, $\xi_{23} = c_2\ddot{q}_{r1} + s_2\dot{q}_2\dot{q}_{r1}$, $\xi_{24} = 0$ and $\xi_{25} = c_{12}$.

Given the desired trajectories x_d , the desired q_d in the joint space can be calculated using CLIK method. For the two-link robot model, the relationship between the velocities in task space and joint space is given as $\dot{x} = J(q)\dot{q} = \begin{bmatrix} -(l_1 s_1 + l_2 s_{12} + l_0 s_{120}) & -(l_2 s_{12} + l_0 s_{120}) \\ l_1 c_1 + l_2 c_{12} + l_0 c_{120} & l_2 c_{12} + l_0 c_{120} \end{bmatrix} \dot{q}$, where l_0 and q_0 are the length and grasping angle of the object. $s_{120} = \sin(q_1 + q_2 + q_0)$ and $c_{120} = \cos(q_1 + q_2 + q_0)$.

In this simulation, the parameters are chosen as follows: $m_1 = 4\text{kg}$, $m_2 = 3\text{kg}$, $l_1 = l_2 = 0.35\text{m}$, $l_{c1} = l_{c2} = 0.175\text{m}$, $I_1 = 0.1225\text{kg}\cdot\text{m}^2$, $I_2 = 0.0919\text{kg}\cdot\text{m}^2$, $l_0 = 0.06\text{m}$ and $q_0 = 45^\circ$. The desired trajectory traces a circular path in the task space and is described by $x_d(1) = 0.33 + 0.1 \sin(0.54 + 3t)$ and $x_d(2) = 0.41 + 0.1 \cos(0.54 + 3t)$ shown in Fig. 2. The initial position of the robot end effector will be specified as $[x(1) = 0.4832 \quad x(2) = 0.4385]$. $\tau_d = [8 \cos(5t) \quad 5 \sin(5t)]$ are considered as time-varying uncertainties in the dynamic model.

Firstly assume that the periods $T_1 = T_2 = 0.4\pi$ are known. Thus we can apply the proposed adaptive learning controller (5)-(7) to handle the periodic

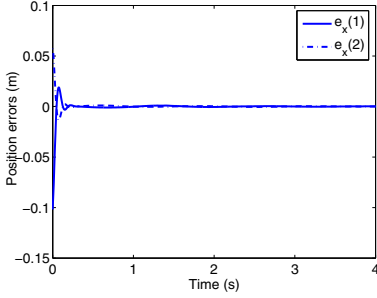


Fig. 3. Tracking error in the task space for time-varying uncertainties with known periods using the adaptive learning controller

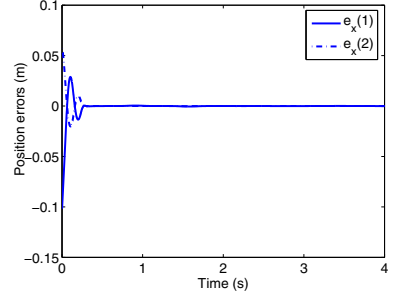


Fig. 4. Tracking error in the task space for time-varying uncertainties with unknown periods using the adaptive robust controller

disturbance τ_d in the robot model. Choosing the parameters in the controller as: $\lambda = 50$, $Q = \text{diag}[50]$, $\gamma_{11} = \gamma_{22} = \gamma_{44} = 10$, $\gamma_{33} = \gamma_{55} = 5$ and $\gamma_1 = \gamma_2 = 50$, the convergence performance is shown in Fig 3. From this figure, it can be seen that the tracking errors in the task space converge to zero in a very short time. This display the validation of the proposed adaptive learning control.

Now we consider that periods T_1 and T_2 are unknown. For this case, the proposed adaptive robust control method in (12)-(14) can be applied to deal with the disturbance by estimating the bound of τ_d . The design parameters in the controller are $\lambda = 50$, $Q = \text{diag}[20]$, $\rho_1 = 1$, $\rho_2 = 156$, $\gamma_{11} = \gamma_{22} = \gamma_{44} = 10$, $\gamma_{33} = \gamma_{55} = 5$ and $\lambda_{11} = \lambda_{22} = 0.001$. Fig 4 shows that despite the periods are not prior, the tracking errors in the task space can still converge to the very small region of zero. Initial fluctuations in the trajectories are caused by parametric uncertainties, but these can be quickly minimized in a very short time such that x is close to the desired trajectories x_d .

5 Conclusion

Firstly we have presented adaptive learning control of uncertain robot manipulator. To deal with the periodic disturbances with known periods, the learning control approaches have been incorporated into the adaptive control system. We have shown that the asymptotic tracking of the desired trajectory is guaranteed. Furthermore we have also considered periodic uncertainties without the prior knowledge of periods or non-periodic uncertainties. By integrating of robust and adaptive control approaches, adaptive robust control design has been shown to yield a finite solution trajectory which can be made arbitrarily close to the reference trajectory. The validity of the two new approaches is confirmed through theoretical analysis and numerical simulations.

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Adaptive Motion Synchronization of Bilateral Teleoperation Systems with Time-Varying Communication Delays*

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Abstract. In this paper, motion synchronization control of bilateral tele-operation system is investigated. Compared with previous passivity framework, the communication delays are assumed to be time-varying. By feedback linearization, the nonlinear dynamics of the tele-operation system is transformed into two sub-systems: local master/slave position control and delayed motion synchronization. We propose new control strategies based on linear matrix inequalities (LMI) and adaptive parameters show that the master-slave tele-operation system is stable under specific LMI conditions. Finally, the simulations are performed to show the effectiveness of the proposed method.

1 Introduction

Bilateral teleoperators are defined as electromechanical machines that enable humans to move, sense, and physically manipulate objects at a distance by the exchange of position, velocity, and/or force information [1]. Bilateral Teleoperation is one of the most interesting and challenging research areas and can be used in a wide range of applications such as outer space exploration [2], handling of toxic materials [3], and minimally invasive surgery. As a result, control technology should be fully developed for teleoperation in all these applications.

Many recent efforts have been based on the passivity methodology [4]. Event-based approaches [5] strive to transmit the actions between master and slave. Predictive methods can be used in such conditions that precise knowledge of the environment [6], the operator [7], or both [8] are required. Communications often involves large distances or impose limited data transfer between the local and the remote sites, as a result, time-delay may happen between the time a command is generated by the operator and the time the command is executed by the remote manipulator.

In this paper, a particular control method based on LMI is proposed to control bilateral teleoperation, which is subjected to communication time delay.

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Our proposed control scheme solves the problem of time delay in teleoperation systems. Simulation results show the validity of the proposed control scheme in master/slave teleoperation systems.

2 Dynamics Description

Let us consider a teleoperator consisting of a pair of n-DOF nonlinear robotic systems

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) + f_m(\dot{q}_m) = F_h + \tau_m \tag{1}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) + f_s(\dot{q}_s) = \tau_s - F_e \tag{2}$$

where q_m, q_s are the n dimension vectors of joint displacement, τ_m, τ_s are the n dimension vectors of applied torque, $M_m(q), C_m(q, \dot{q}), G_m(q_m)$ are coefficient matrixes related to robotic systems. $f_m(\dot{q}_m)$ and $f_s(\dot{q}_s)$ are the external friction force vectors. Also, F_h is the human operator force and F_e is the environmental force acting on the slave robot when it contacts the environment.

We first study the case of free motion, and assume that the human-operator force $F_h(t)$ and the environmental force $F_e(t)$ are zero. The bilateral tele-operator with the time-delay d_t is said to state synchronize if

$$\begin{aligned} \lim_{t \rightarrow \infty} \|q_m(t - d_t) - q_s(t)\| &= \lim_{t \rightarrow \infty} \|\dot{q}_m(t - d_t) - \dot{q}_s(t)\| = 0 \\ \lim_{t \rightarrow \infty} \|q_s(t - d_t) - q_m(t)\| &= \lim_{t \rightarrow \infty} \|\dot{q}_s(t - d_t) - \dot{q}_m(t)\| = 0 \end{aligned}$$

Assumption 2.1. *The size of the unknown time delay is time-varying and bounded by a known constant, i.e., $0 \leq d_t(t) \leq d$ and $\dot{d}_t(t) \leq d_d \leq 1$, with the known constants d and d_d .*

3 Motion Synchronizaion of Master-Slave Tele-operation System

Define the filtered tracking errors as

$$r_j = \dot{q}_j + \Lambda_j q_j \tag{3}$$

where Λ_j is a positive diagonal, and $j = m, s$. Moreover, it is easy to have the following computable signals $\dot{q}_{jr} = -\Lambda_j q_j$. Since $\dot{q}_j = -\Lambda_j q_j + r_j$ and $\ddot{q}_j = -\Lambda_j \dot{q}_j + \dot{r}_j, j = m, s$, let

$$\mu_j = M_j \ddot{q}_{jr} + C_j \dot{q}_j + G_j + f_j(\dot{q}_j) \tag{4}$$

Equations (1) and (2) becomes

$$M_m(q_m)\dot{r}_m = \tau_m - \mu_m \quad , \quad M_s(q_s)\dot{r}_s = \tau_s - \mu_s \tag{5}$$

Define the following nonlinear feedback

$$\tau_m = M_m(q)(U_m + M_m^{-1}(q)\mu_m) \quad , \quad \tau_s = M_s(q)(U_s + M_s^{-1}(q)\mu_s) \quad (6)$$

where U_m and U_s are auxiliary control inputs to be defined later, therefore, the close loop system for q_m and q_s sub-system becomes

$$\dot{r} = U \quad (7)$$

where $r = [r_m^T, r_s^T]^T$, $U = [U_m^T, U_s^T]^T$.

Define the coordination errors between the master and slave robots as $e_m(t) = q_m(t - d_t) - q_s(t)$, $e_s(t) = q_s(t - d_t) - q_m(t)$. It is easy to have

$$\dot{e}_m(t) = -\Lambda_m e_m(t) + \Lambda_m q_m(t - d_t)\dot{d}_t + r_m(t - d_t)[1 - \dot{d}_t] - r_s(t) \quad (8)$$

$$\dot{e}_s(t) = -\Lambda_s e_s(t) + \Lambda_s q_s(t - d_t)\dot{d}_t + r_s(t - d_t)[1 - \dot{d}_t] - r_m(t) \quad (9)$$

where $\Lambda_m = \Lambda_s$.

Let $e = [e_m, e_s]^T$, $\Lambda = \text{diag}[\Lambda_m, \Lambda_s]$, and $r = [r_m, r_s]^T$, then we have

$$e = \begin{bmatrix} -\Lambda_m & 0 \\ 0 & -\Lambda_s \end{bmatrix} \begin{bmatrix} e_m \\ e_s \end{bmatrix} + \begin{bmatrix} r_m(t - d_t)[1 - \dot{d}_t] - r_s(t) \\ r_s(t - d_t)[1 - \dot{d}_t] - r_m(t) \end{bmatrix} + \begin{bmatrix} \Lambda_m q_m(t - d_t)\dot{d}_t \\ \Lambda_s q_s(t - d_t)\dot{d}_t \end{bmatrix}$$

We could build up the following augmented system as

$$\begin{aligned} \dot{X} = [\dot{X}_1^T \quad \dot{X}_2^T]^T &= \begin{bmatrix} -\Lambda_m & 0 & 0 & -I \\ 0 & -\Lambda_s & -I & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} e_m \\ e_s \\ r_m \\ r_s \end{bmatrix} + \begin{bmatrix} 0 & 0 & [1 - \dot{d}_t]I & 0 \\ 0 & 0 & 0 & [1 - \dot{d}_t]I \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} e_m(t - d_t) \\ e_s(t - d_t) \\ r_m(t - d_t) \\ r_s(t - d_t) \end{bmatrix} \\ &+ \begin{bmatrix} \Lambda_m q_m(t - d_t)\dot{d}_t \\ \Lambda_s q_s(t - d_t)\dot{d}_t \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ M_m^{-1}(q_m)(\tau_m - \mu_m) \\ M_s^{-1}(q_s)(\tau_s - \mu_s) \end{bmatrix} \quad (10) \end{aligned}$$

which can be described by brief form

$$\dot{X} = A_1 X + A_2 X(t - d_t) + U + W \quad (11)$$

with $U = [0, 0, M_m^{-1}(q_m)(\tau_m - \mu_m), M_s^{-1}(q_s)(\tau_s - \mu_s)]^T$, $A_1, A_2 \in R^{4n \times 4}$, $X, W, U \in R^{4n \times 1}$.

The proposed control for the system is given as

$$U = \begin{bmatrix} 0 \\ 0 \\ U_m \\ U_s \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ K_1 r_m(t) + K_2 r_s(t - d_t) \\ K_3 r_m(t - d_t) + K_4 r_s(t) \end{bmatrix} \quad (12)$$

where $K_i \in R^{n \times n}$ is a diagonal positive.

As the precise values of parameters $M_j, C_j, G_j, f_j, j = m, s$ in dynamical models (1) and (2) are difficult to acquire, it is assumed that actual value M_j ,

C_j , G_j , f_j can be separated as nominal parts denoted by \bar{M}_j^0 , \bar{C}_j^0 , G_j^0 and f_j^0 and uncertain parts denoted by ΔM_j , $\Delta \bar{C}_j$, $\Delta \bar{G}_j$ and Δf_j , respectively. These variables satisfy the following relationships:

$$M_j = M_j^0 + \Delta M_j, \quad C_j = C_j^0 + \Delta C_j, \quad G_j = G_j^0 + \Delta G_j, \quad f_j = f_j^0 + \Delta f_j$$

Therefore, we proposed the adaptive control law as

$$\tau_m = \tau_m^0 + \Delta \tau_m, \quad \tau_s = \tau_s^0 + \Delta \tau_s \quad (13)$$

where $\Delta \tau_m$ and $\Delta \tau_s$ are used to compensate the dynamics uncertainty.

The close loop can be described as

$$\begin{aligned} \dot{X} = \begin{bmatrix} \dot{e}_m \\ \dot{e}_s \\ \dot{r}_m \\ \dot{r}_s \end{bmatrix} &= \begin{bmatrix} -A_m & 0 & 0 & -I \\ 0 & -A_s & -I & 0 \\ 0 & 0 & K_1 & 0 \\ 0 & 0 & 0 & K_4 \end{bmatrix} \begin{bmatrix} e_m \\ e_s \\ r_m \\ r_s \end{bmatrix} + \begin{bmatrix} 0 & 0 & [1 - \dot{d}(t)]I & 0 \\ 0 & 0 & 0 & [1 - \dot{d}(t)]I \\ 0 & 0 & 0 & K_2 \\ 0 & 0 & K_3 & 0 \end{bmatrix} \begin{bmatrix} e_m(t - d_t) \\ e_s(t - d_t) \\ r_m(t - d_t) \\ r_s(t - d_t) \end{bmatrix} \\ &+ \begin{bmatrix} \Lambda_m q_m(t - d_t) \dot{d}_t \\ \Lambda_s q_s(t - d_t) \dot{d}_t \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -U_m + M_m^{-1} \tau_m - M_m^{-1}(q_m) \mu_m \\ -U_s + M_s^{-1} \tau_s - M_s^{-1}(q_s) \mu_s \end{bmatrix} \end{aligned}$$

It is easy to rewrite the last term as

$$-U_j + M_j^{-1} \tau_j - M_j^{-1}(q_j) \mu_j = (M_j^{-1} M_j^0 - I) U_j + M_j^{-1} \Delta \tau_j - M_j^{-1}(q_j) \Delta \mu_j$$

which can be decoupled into two sub-systems as

X_1 subsystem:

$$\dot{e} = A_{11} e + A_{12} r + A_{13} r(t - d_t) + W(t - d_t) \quad (14)$$

$$A_{11} = \begin{bmatrix} -A_m & 0 \\ 0 & -A_s \end{bmatrix}, \quad A_{12} = \begin{bmatrix} 0 & -I \\ -I & 0 \end{bmatrix}, \quad A_{13} = \begin{bmatrix} [1 - \dot{d}_t]I & 0 \\ 0 & [1 - \dot{d}_t]I \end{bmatrix}$$

$$W(t - d_t) = \begin{bmatrix} \Lambda_m q_m(t - d_t) \dot{d}_t \\ \Lambda_s q_s(t - d_t) \dot{d}_t \end{bmatrix}$$

X_2 subsystem:

$$\dot{r} = A_{21} r + A_{22} r(t - d_t) + \Xi \quad (15)$$

$$A_{21} = \begin{bmatrix} K_1 & 0 \\ 0 & K_4 \end{bmatrix}, \quad A_{22} = \begin{bmatrix} 0 & K_2 \\ K_3 & 0 \end{bmatrix}$$

$$\Xi = \begin{bmatrix} \Xi_m \\ \Xi_s \end{bmatrix} = \begin{bmatrix} (M_m^{-1} M_m^0 - I) U_m + M_m^{-1} \Delta \tau_m - M_m^{-1}(q_m) \Delta \mu_m \\ (M_s^{-1} M_s^0 - I) U_s + M_s^{-1} \Delta \tau_s - M_s^{-1}(q_s) \Delta \mu_s \end{bmatrix}$$

4 Stability Analysis

4.1 X_2 Subsystem

To expand the applications of the control strategies we proposed, a time-varying delay system is taken into our consideration. Consider the following dynamical system with time-varying delay d_t .

$$\dot{r}(t) = A_{21}r(t) + A_{22}r(t - d_t) + \Xi \tag{16}$$

Theorem 1. *The time-delay system (16) is asymptotically stable for any time delay d_t satisfying Assumption 2.1, if there exist the positive definite P , and $Q \geq 0$ such that the LMI in the inequality (17) holds.*

$$\begin{pmatrix} \Gamma & 0 & d\Lambda_{12} + \Lambda_{23} - \Lambda_{13} + A_{22}P \\ * & d\Lambda_{33} & 0 \\ * & * & d\Lambda_{22} - 2\Lambda_{23} - (1 - d_d)Q \end{pmatrix} < 0 \tag{17}$$

$$\Gamma = PA_{21} + A_{21}^T P + Q + d\Lambda_{11} + 2\Lambda_{13} \tag{18}$$

Proof: Define the Lyapunov-Krasovskii functionals as

$$V = V_1 + V_2 + V_3 + V_4 + V_5 \tag{19}$$

where $V_1 = r^T P r$, $V_2 = \tilde{\Theta}^T \Omega^{-1} \tilde{\Theta}$, $V_3 = \int_{t-d_t}^t r^T Q r ds$, $V_4 = \int_0^d (d - \beta) \dot{r}^T (t - \beta) \Lambda_{33} \dot{r} (t - \beta) d\beta$, $V_5 = \int_0^t \int_{\beta-d(\beta)}^\beta \zeta^T \Lambda \zeta d\alpha d\beta$, where $\tilde{\Theta} = \Theta - \hat{\Theta}$, and $\Theta = [\Theta_m^T, \Theta_s^T]^T$, $\Theta_m = [\Theta_{m1}, \dots, \Theta_{m7}]^T$, $\Theta_s = [\Theta_{s1}, \dots, \Theta_{s7}]^T$, $\Omega = \text{diag}[\omega_{ji}]$, $j = m, s$, $i = 1, \dots, 7$, and $\zeta = [r^T(\beta) \ r^T(\beta - d(\beta)) \ \dot{r}^T(\alpha)]^T$,

$$\Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} \\ * & \Lambda_{22} & \Lambda_{23} \\ * & * & \Lambda_{33} \end{bmatrix} = \Lambda^T > 0. \text{ The matrices } P, \Lambda_{ij}, A_{22} \text{ are symmetric.}$$

Considering the derivatives of V_1 and V_2 , we have

$$\begin{aligned} \dot{V}_1 + \dot{V}_2 &= r^T P \dot{r} + \dot{r}^T P r + 2\tilde{\Theta}^T \Omega^{-1} \dot{\tilde{\Theta}} \\ &= r^T (A_{21}^T P + P A_{21}) r + r^T (t - d_t) (A_{22}^T P + A_{22} P^T) r \\ &\quad + 2 \begin{bmatrix} r_m^T & r_s^T \end{bmatrix} \begin{bmatrix} P_m & 0 \\ 0 & P_s \end{bmatrix} \begin{bmatrix} \Xi_m \\ \Xi_s \end{bmatrix} + 2\tilde{\Theta}^T \Omega^{-1} \dot{\tilde{\Theta}} \\ &= r^T (A_{21}^T P + P A_{21}) r + r^T (t - d_t) (A_{22}^T P + A_{22} P^T) r \\ &\quad + 2r_m^T P_m ((M_m^{-1} M_m^0 - I) U_m + M_m^{-1} \Delta \tau_m - M_m^{-1} (q_m) \Delta \mu_m) \\ &\quad + 2r_s^T P_s ((M_s^{-1} M_s^0 - I) U_s + M_s^{-1} \Delta \tau_s - M_s^{-1} (q_s) \Delta \mu_s) + 2\tilde{\Theta}^T \Omega^{-1} \dot{\tilde{\Theta}} \end{aligned} \tag{20}$$

Assumption 4.1. *The known positive parameters b_m, b_s, p_m and p_s satisfy $b_m \leq \lambda_{\min}(M_m^{-1})$ and $\lambda_{\max}(P_m) \leq p_m$, $b_s \leq \lambda_{\min}(M_s^{-1})$ and $\lambda_{\max}(P_s) \leq p_s$, that is $x^T b_m I x \leq x^T M_m^{-1} x$, $x^T p_m I x \geq x^T P_m x$, $x^T b_s I x \leq x^T M_s^{-1} x$, $x^T p_s I x \geq x^T P_s x$ with any vectors.*

Consider the following controls as

$$\Delta \tau_m = -\frac{b_m}{p_m} \text{sgn}(r_m) \hat{\Phi}_m, \quad \Delta \tau_s = -\frac{b_s}{p_s} \text{sgn}(r_s) \hat{\Phi}_s \tag{21}$$

where $\hat{\Phi}_j = \hat{\Theta}_j \Psi_j$, $\hat{\Theta}_j = [\hat{\Theta}_{j1}, \dots, \hat{\Theta}_{j7}]^T$, $\Psi_j = [\|\ddot{q}_{jr}\|, \|\dot{q}_j\|, \|\dot{q}_j\|^2, 1, 1, \|\dot{q}_j\|, \|\mathbf{U}_j\|]$, $\text{sgn}(r) = \frac{r}{\|r\|}$, which are adaptively tuned according to

$$\dot{\hat{\Theta}}_{ji} = -\alpha_{ji} \hat{\Theta}_{ji} + \omega_{ji} \|r_j\| \Psi_{ji}, \quad \hat{\Theta}_{ji}(0) > 0 \tag{22}$$

with $\alpha_{ji} > 0$ being designed parameters and satisfying

$$\lim_{t \rightarrow \infty} \alpha_{ji} = 0 \quad , \quad \int_0^{\infty} \alpha_{ji}(t) dt = \varrho_{\alpha} < \infty \quad (23)$$

with finite constant ϱ_{α} , and $\omega_{ji} > 0$ is design parameter, $j = m, s$.

Integrating (21), we can rewrite (20) as

$$\begin{aligned} \dot{V}_1 + \dot{V}_2 \leq & r^T (A_{21}^T P + P A_{21}) r + r^T (t - d_t) (A_{22}^T P + A_{22}^T P^T) r + 2\tilde{\Theta}^T \Omega^{-1} \dot{\tilde{\Theta}} \\ & + 2\|r_m\| \|P_m\| \|M_m^{-1} M_m^0 - I\| \|U_m\| + 2r_m^T P_m M_m^{-1} \Delta \tau_m \\ & + 2\|r_m\| \|P_m\| \|M_m^{-1}(q_m)\| \|\Delta \mu_m\| + 2\|r_s\| \|P_s\| \|M_s^{-1} M_s^0 - I\| \|U_s\| \\ & + 2r_s^T P_s M_s^{-1} \Delta \tau_s + 2\|r_s\| \|P_s\| \|M_s^{-1}(q_s)\| \|\Delta \mu_s\| \end{aligned} \quad (24)$$

Consider $\|P_j\| \|M_j^{-1}(q_j)\| \|\Delta \mu_j\| = \|P_j\| \|M_j^{-1}(q_j)\| \|\Delta M_j\| \|\ddot{q}_{jr}\| + \|P_j\| \|M_j^{-1}(q_j)\| \|\Delta C_j\| \|\dot{q}_j\| + \|P_j\| \|M_j^{-1}(q_j)\| \|\Delta G_j\| + \|P_j\| \|M_j^{-1}(q_j)\| \|\Delta f_j(\dot{q}_j)\|$, $j = m, s$. Let $\|P_j\| \|M_j^{-1}(q_j)\| \|\Delta M_j\| \leq \Theta_{j1}$, $\|P_j\| \|M_j^{-1}(q_j)\| \|\Delta C_j\| \leq \Theta_{j2} + \Theta_{j3} \|\dot{q}_j\|$, $\|P_j\| \|M_j^{-1}(q_j)\| \|\Delta G_j\| \leq \Theta_{j4}$, $\|P_j\| \|M_j^{-1}(q_j)\| \|\Delta f_j(\dot{q}_j)\| \leq \Theta_{j5} + \Theta_{j6} \|\dot{q}_j\|$, $\|P_j\| \|M_j^{-1} M_j^0 - I\| \leq \Theta_{j7}$ with unknown constants $\Theta_{j1}, \dots, \Theta_{j7}$. Moreover, since P_j and M_j are positive definite, it is easy to have

$$r_j^T P_j M_j^{-1} \Delta \tau_j = -r_j^T P_j M_j^{-1} \frac{b_j}{p_j} \text{sgn}(r_j) \hat{\Phi}_j \leq -\|r_j\| \|\hat{\Phi}_j\| \quad (25)$$

we have

$$\begin{aligned} \dot{V}_1 + \dot{V}_2 \leq & r^T (A_{21}^T P + P A_{21}) r + r^T (t - d_t) (A_{22}^T P + A_{22}^T P^T) r \\ & + \sum_{j=m,s} \{ \|r_j\| \Theta_j^T \Psi_j - \|r_j\| \|\hat{\Phi}_j\| + 2 \sum_{i=1}^7 \tilde{\Theta}_{ji} \left[\frac{\alpha_{ji}}{\omega_{ji}} \hat{\Theta}_{ji} - \|r_j\| \|\Psi_{ji}\| \right] \} \\ \leq & r^T (A_{21}^T P + P A_{21}) r + r^T (t - d_t) (A_{22}^T P + A_{22}^T P^T) r \\ & - 2 \sum_{j=m,s} \sum_{i=1}^7 \frac{\alpha_{ji}}{\omega_{ji}} (\hat{\Theta}_{ji} - \frac{1}{2} \Theta_{ji})^2 + 2 \sum_{j=m,s} \sum_{i=1}^7 \frac{\alpha_{ji}}{4\omega_{ji}} \Theta_{ji}^2 \end{aligned} \quad (26)$$

Consider Assumption 2.1, the derivative of V_3 satisfies

$$\dot{V}_3 \leq r^T(t) Q r(t) - (1 - d_d) r^T(t - d_t) Q r(t - d_t) \quad (27)$$

Considering the derivative of V_4 , we have

$$\dot{V}_4 = d \dot{r}^T(t) A_{33} \dot{r}(t) - \int_{t-d}^t \dot{r}^T(\alpha) A_{33} \dot{r}(\alpha) d\alpha \quad (28)$$

The derivative of V_5 is

$$\begin{aligned} \dot{V}_5 \leq & d r^T(t) A_{11} r(t) + 2d r^T(t) A_{12} r(t - d_t) + d r^T(t - d_t) A_{22} r(t - d_t) + 2r^T(t) A_{13} r(t) \\ & - 2r^T(t) A_{13} r(t - d_t) + 2r^T(t - d_t) A_{23} r(t) - 2r^T(t - d_t) A_{23} r(t - d_t) \\ & + \int_{t-d}^t \dot{r}^T(\alpha) A_{33} \dot{r}(\alpha) d\alpha \end{aligned} \quad (29)$$

Finally, combining the derivatives (26), (27), (28), and (29), we have

$$\dot{V} \leq \begin{bmatrix} r(t) \\ \dot{r}(t) \\ r(t-d_t) \end{bmatrix}^T \mathcal{Y} \begin{bmatrix} r(t) \\ \dot{r}(t) \\ r(t-d_t) \end{bmatrix} + 2 \sum_{j=m,s} \sum_{i=1}^7 \frac{\alpha_{ji}}{4\omega_{ji}} \Theta_{ji}^2 \tag{30}$$

where

$$\mathcal{Y} = \begin{bmatrix} \Gamma & 0 & dA_{12} + A_{23} - A_{13} + A_{22}P \\ * & dA_{33} & 0 \\ * & * & dA_{22} - 2A_{23} - (1-d_d)Q \end{bmatrix}, \quad \Gamma = PA_{21} + A_{21}^T P + Q + dA_{11} + 2A_{13}$$

Using the Schur complement, considering (23), we find that \dot{V} is negative as long as the inequalities $\mathcal{Y} \leq 0$ is hold, which implies that the system is asymptotically stable.

4.2 X_1 Subsystem

From previous stability of system X_2 , we know that, the signals $r_m(t)$, $r_s(t)$ are stable. Similar to X_2 subsystem, the time-varying delays in system X_1 also can be dealt with LMI, we assume that the system(14) is in the zero initial conditions, the H_∞ performance is defined as follows:

Definition 1. Given a constant scalar $\gamma > 0$, we say that system (14) is stable with disturbance attenuation level γ under zero initial condition ($e(0) = 0$), only if

$$J = \int_0^T [e^T(t)e(t) - \gamma^2 \zeta^T(t)\zeta(t)]dt < 0 \tag{31}$$

where $\zeta(t) \triangleq [r^T(t) \ r^T(t-d_t) \ W^T(t-d_t)]^T$.

Theorem 2. If there exist $2n \times 2n$ positive definite matrix P , positive scalars γ such that the following LMI holds, then we could conclude that system(14) is stable with disturbance attenuation level γ .

$$\Pi = \begin{bmatrix} A_{11}^T P + PA_{11} + I PA_{12} & 0 & P \\ * & -\gamma^2 I & 0 \\ * & * & (-\gamma^2 + 2\varepsilon)I \\ * & * & * & -\gamma^2 I \end{bmatrix} < 0 \tag{32}$$

Proof.

$$J = \int_0^T [e^T(t)e(t) - \gamma^2 \zeta^T(t)\zeta(t)]dt \tag{33}$$

we define a new variable $\eta(t) = [e(t), r(t), r(t-d(t)), W(t-d(t))]^T$

Choose $V(e(t), t) = e^T(t)Pe(t)$, since we have defined that $\Lambda_m = \Lambda_s$, then

$$\dot{V}(e(t), t) = e^T(t)[A_{11}^T P + PA_{11}]e(t) + 2e^T(t)PA_{12}r(t) + 2e^T(t)PA_{13}r(t - d(t)) + 2e^T(t)PW(t - d(t))$$

As the initial state is zero, considering $\eta(t)$ we defined and using Shur-complement lemma, we have the following result with no difficulty

$$J = \int_0^T [e^T(t)e(t) - \gamma^2 \zeta^T(t)\zeta(t) + \dot{V}(e(t), t)]dt - V(e(T)) \leq \int_0^T \eta^T(t)\Pi\eta(t)dt - V(e(T))$$

Owing to (32), we obtain

$$J = \int_0^T [e^T(t)e(t) - \gamma^2 \zeta^T(t)\zeta(t)]dt < 0$$

That completes the proof.

5 Simulation Studies

To verify the effectiveness of the proposed control algorithm, let us consider 2-DOF manipulators, and we assume that there exist two terms of masters and slaves in the system. In (1) and (2), $M_m(q) = M_s(q) = \begin{bmatrix} M_{11} & M_{12} \\ & M_{22} \end{bmatrix}$, $C_m(q, \dot{q}) = C_s(q, \dot{q}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$, $M_{11} = (2l_1 \cos q_2 + l_2)l_2m_2 + l_1^2(m_1 + m_2)$, $M_{12} = l_2^2m_2 + l_1l_2m_2 \cos q_2$, $M_{22} = l_2^2m_2$, $C_{11} = -l_1l_2m_2 \sin q_2\dot{q}_2$, $C_{21} = l_1l_2m_2 \sin q_2$, $C_{12} = -l_1l_2m_2 \sin q_2(\dot{q}_1 + \dot{q}_2)$, $C_{22} = 0$.

In the simulation, we choose the related parameters as $m_1 = m_2 = 2.0kg$, $l_1 = l_2 = 0.6m$ for the master manipulator, and $m_1 = m_2 = 1.0kg$, $l_1 = l_2 = 0.4m$ for the slave manipulator, $g = 9.8m/s^2$, $\Lambda_m = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix}$, $\Lambda_s = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix}$. Through transformations of (4) and (6), the feedback gain parameters in (12) are chosen as follows: $k_1 = \begin{bmatrix} -5 & -0.2 \\ 0.1 & -3 \end{bmatrix}$, $k_2 = \begin{bmatrix} -0.5 & 0.4 \\ 0.1 & -0.2 \end{bmatrix}$, $k_3 = \begin{bmatrix} 0.4 & 0.2 \\ 0.1 & -0.2 \end{bmatrix}$, $k_4 = \begin{bmatrix} -2.8 & 0.1 \\ -0.3 & -4.5 \end{bmatrix}$.

The upperbound of the value and the derivative of the time-varying delay are $d = 0.2, d_d = 0.62$, respectively. In the simulation, we might as well choose time delay as $d_t(t) = 0.2\sin^2t$. From the system parameters chosen above, we can obtain the following corresponding matrices for X_2 subsystem

$$A_{21} = \begin{bmatrix} -5 & -0.2 & 0 & 0 \\ 0.1 & -3 & 0 & 0 \\ 0 & 0 & -2.8 & 0.1 \\ 0 & 0 & -0.3 & -4.5 \end{bmatrix}, A_{22} = \begin{bmatrix} 0 & 0 & -0.5 & 0.4 \\ 0 & 0 & 0.1 & -0.2 \\ -0.5 & 0.1 & 0 & 0 \\ 0.4 & -0.2 & 0 & 0 \end{bmatrix}.$$

Using the LMI toolbox in the MATLAB, we can solve (17) and obtain $P = \begin{bmatrix} 15.0682 & 0.2934 & 0.0063 & 0.0038 \\ 0.2934 & 15.4631 & 0.0116 & -0.0098 \\ 0.0063 & 0.0116 & 15.0665 & 0.2036 \\ 0.0038 & -0.0098 & 0.2036 & 15.4440 \end{bmatrix}$, $Q = \begin{bmatrix} 13.6693 & 0.0021 & 0.0194 & 0.0397 \\ 0.0021 & 13.6575 & 0.0424 & -0.0467 \\ 0.0194 & 0.0424 & 13.6427 & -0.0024 \\ 0.0397 & -0.0467 & -0.0024 & 13.6760 \end{bmatrix}$.

We assume the nominal dynamics of master and slave robot are with 50% uncertainty, and choose $\omega_i = 0.5$, $\alpha_i = \delta = 1/(t + 1)^2$, $\rho = 1$, $b_m = b_s = 1$, $p_m = p_s = 20$, $[\hat{\theta}_{m1}(0), \dots, \hat{\theta}_{m7}(0)]^T = [\hat{\theta}_{s1}(0), \dots, \hat{\theta}_{s7}(0)]^T = [0.5, \dots, 0.5]^T$. The initial state for X_2 is assumed to be $r(s) = [0.4\sin s, 0.7\cos s, 0.3\sin^2 s, 0.6\cos^2 s]^T$. Then the trajectories of the states X_2 is shown in Fig. 1.

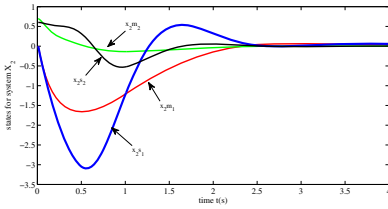


Fig. 1. The states of X_2 subsystem

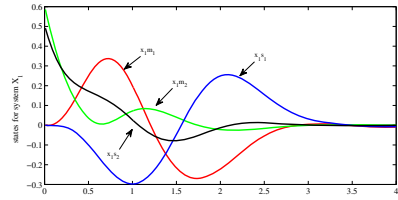


Fig. 2. The states of X_1 subsystem

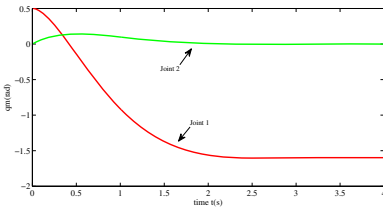


Fig. 3. Trajectories of the mater robot

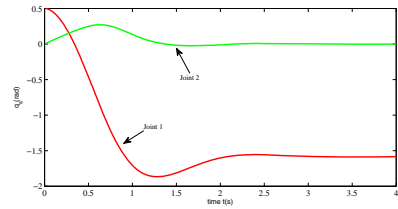


Fig. 4. Trajectories of the slave robot

Similarly, we obtain the parameters for X_1 subsystem:

$$A_{11} = \begin{bmatrix} -4.1 & 0 & 0 & 0 \\ 0 & -3.4 & 0 & 0 \\ 0 & 0 & -2.3 & 0 \\ 0 & 0 & 0 & -2.8 \end{bmatrix}, A_{12} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}$$

and $A_{13} = (1 - 0.2\sin 2t) \times I_{4 \times 4}$. We use the LMI toolbox to solve (32) and obtain a group of appropriate solutions

$$\mathcal{P} = \begin{bmatrix} 1.6226 & 0 & 0 & 0 \\ 0 & 1.9154 & 0 & 0 \\ 0 & 0 & 2.5899 & 0 \\ 0 & 0 & 0 & 2.2454 \end{bmatrix},$$

and we select $\gamma = 3.8129$. The initial state for X_1 is chosen as $X_1(s) = [0.8\sin s, 0.6\cos s, 0.7\sin^2 s, 0.5\cos^2 s]^T$.

Then the trajectory of system X_1 is illustrated in Fig 2. The positions for the master and slave robots are shown in Fig. 3 and Fig 4. And we could easily see the satisfactory performance of the system.

6 Conclusions

In this paper, motion synchronization control of bilateral tele-operation system is investigated. By feedback linearization, the nonlinear dynamics of the tele-operation system is transformed into two sub-systems: local master/slave position control and delayed motion synchronization. We propose new control strategies based on linear matrix inequalities and adaptive parameters. By choosing Lyapunov Krasovskii function, we show that the master-slave teleoperation system is asymptotically stable under specific LMI conditions.

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Design of Robot Assisted Observation System for Therapy and Education of Children with Autism

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Abstract. Recently, a robot mediated therapy was given attention in support of the education and rehabilitation of children with autism. In this paper, we design and develop a robot assisted test-bed system, which provides efficient observations and analysis methods for children with autism during a free play session with robots. The test-bed system consists of a portable handheld device and a remote server. The handheld device helps a therapist to input and analyze observed results of children's play, and the remote server stores recorded video and audio information using a database program. For the robot platforms for proposed test-bed system, we use animal-type devices, which are familiar and effective for children with autism. The observed interaction between the robot and children is transmitted in real-time to the remote server. Thereafter, if it is needed, this system can provide the therapist with analyzed monitoring information for further educational treatments. For the actual service trial of the proposed system, we have implemented a specialized kindergarten for children with autism and performed several experiments. Results show that the proposed test-bed system provides not only easy and quantitative observation methods, but also efficient analyses for monitoring positive interactions between children with autism and robot systems.

Keywords: test-bed system, robot assisted therapy, monitoring system, children with autism, human robot interactions.

1 Introduction

Symptoms of Autistic Spectrum Disorder (ASD) frequently and diversely occur worldwide. Conceptually, ASD is a hindrance of neural development characterized by impaired social interaction and communication, and by restricted and repetitive behavior. Children with autism usually keep to themselves and cannot communicate without special help from other people. They also have difficulty linking words to

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their meanings, which is frustrating if they are not able to come up with the right words to express their own thoughts. This hindrance not only prevents people from performing social and interactive activities with other people, but also the ASD patient and his or her family experience significant inconvenience. In order to overcome this social problem, convergence robot technologies with wireless and wired networking services are increasingly used in rehabilitation and education [1]–[4]. One of main advantages of robot assisted therapy is that the use of robot systems provides more reliable and comport treatments than traditional human assisted behavior because the therapist can control the environment and easily predict the results of interactions between the robots and children with autism. These robot systems, with their various interactive operations, may mitigate a refusal response and offer more positive stimuli. Moreover, contrary to traditional therapy approaches, which significantly depend on subjective descriptions by the therapist, the use of robotic systems provides simple and objective descriptive methods by using constrained and predictable scenarios during the therapy procedure.

Although there are many related works that address the importance of robot assisted therapy and propose novel interactive mechanisms, little work has been done to help the therapist to monitor the expected interactive activities between robots and children with autism. Including this problem, the most challenging issues of this paper are illustrated as follows.

- 1) The therapist needs environments in which they can concentrate only on therapy and education, minimizing overhead such as writing in an observation diary and managing other devices related to the robot systems;
- 2) The therapy test-bed with the robot system should record and store the whole therapy processes to establish a therapy database system, which could provide not only behavior analysis, but also an educational prediction using analyzed patterns for children with autism;
- 3) In order to observe the whole therapy process, the therapist requires an efficient and user-friendly monitoring interface between him/her and the robot assisted test-bed. After gathering and analyzing observed information, the therapist is able to execute further operations for proper treatments; and
- 4) When the therapist observes the interactions between the robots and children, the monitoring system should provide quantitative and objective measurement mechanisms in order to exclude obscure diagnosis and help other experts to usefully analyze the measured information.

In order to tackle above issues, we propose the design and implementation of a robot assisted observation system, which provides more efficient monitoring and analyzing of interactions between robots and children with autism. The implemented test-bed system consists of six pet robots, a handheld device to input observed information of interactions, an internet camera with a microphone to record the whole therapy scene, and a remote server to maintain the therapy database. The information measured by the therapist using handheld device is transmitted to the remote server through a wireless network. The server creates a database schema for further operations such as inserting, removing, and modifying the data.

In Section 2 of this paper, we review several related works on robot assisted therapy systems. Section 3 explains the proposed test-bed system for monitoring interactions between robots and children with autism. In Section 4, we discuss the trial results of our proposed test-bed system that has been performed in the kindergarten for children with autisms. Finally, concluding remarks and future works are given in Section 5.

2 Related Works

Over the last decade, research has shown that robotics and computer assisted therapy are very promising technologies for ASD diagnosis, intervention, and rehabilitation. A number of related monitoring systems have also been proposed. The Abaris [5] is one of the most representative systems that allow monitoring. It also describes the therapy process for children with autism. This system allows not only an automated capturing interface with various networked devices, such as a webcam, a microphone and a digital pen, but also displays a graphical interface for data analysis with the ability to review therapy sessions. Another example is KidCam [6], which allows families to capture videos and photographs of their children and monitor their activities from the remote area through the IEEE 802.11 wireless channel. The CareView system [7] utilizes a set of visualization interfaces with numeric and qualitative records for the patient's condition in order to reduce legacy narrative records. For the standardization, ISO/IEEE 11073 [8] describes the specifications of personal health devices for monitoring physical health, which provides the basic system architecture to design the monitoring system.

Although these works demonstrate effective monitoring schemes for children, they differ from our system by not focusing on providing interactions between robotic systems and children with autism during the monitoring procedure. Thus, they cannot extract the desired attributes and positive effects of robot assisted therapy.

3 Design of Test-Bed System

3.1 Architecture of Test-Bed System

The test-bed system was developed for a specialized kindergarten for developmentally disabled children in Daegu City, Korea. We chose a quiet room that is used for ordinary class work and training, in order to provide a comfortable and stable monitoring environment. The room had one door and two windows, and measured 4.6m by 4.7m. The conceptual test-bed topology of the classroom and pictures of the corresponding components are illustrated in Figure 1 and 2, respectively.

As shown in Figure 1, the test-bed system consisted of an assisted robot system, a PDA (Personal Digital Assistance) device, a remote server, an AP (Access Point), a switching hub, and video cameras with microphones. Once the robot system was prepared for therapy procedure, the therapist observed the whole interactions between the children and robot system. Whenever the therapist imputed observed data, using a PDA, it was immediately transmitted to the remote server through the IEEE

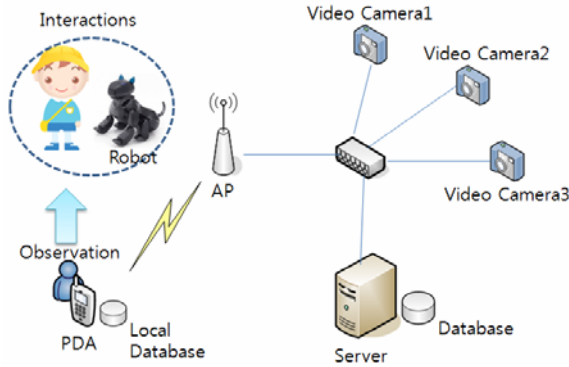


Fig. 1. Topology of test-bed



Fig. 2. Components for observation (server, video camera, and classroom)

802.11b/g wireless channel. Three video cameras with different positions were installed to monitor the entire therapy experiments and their recorded data was transmitted to the server. Needless to say, if the therapist wanted to capture more dynamic scenery, she/he installed additional video cameras. However, contrary to the input via PDA, video data transmission used wired LAN (Local Area Network), since multimedia traffic requires high network bandwidth. Physically, each video camera was installed in hard-to-reach places, such as on top of furniture and on the ceiling, to prevent any disturbances by the children such as wrong input. Similarly, the server was located in a dedicated cabinet as shown in Figure 2.

3.2 Interactions between Robots and Children with Autism







As participants in the therapy experiments, the teacher and therapist chose three children with autism in the kindergarten in which the test-bed system was located. Each child had various disabilities and difficulties of social interactions. They were asked to play with several pet-type robot systems, which were all existing commercial products for basic social interactions [9]-[14]. Information on all of the children and robot systems are described in Table 1 and Table 2, respectively.

The experiment was conducted three times each week during a three-month period, totally fourteen trials. The experiment for one child lasted approximately 20 minutes, (allocating three minutes each for six robots). A therapist and an assistant teacher

Table 1. Personal information of selected children

Characteristics	Child A	Child B	Child C
Sex	Male	Male	Male
Age	6 years	5 years	6 years
Expressive Language Ability	11 month	19 month	11 month
Receptive Language Ability	10 month	20 month	14 month

Table 2. Pet type robot systems for interactions

Robot System	Description	Robot System	Description
 <p>PARO</p>	<ul style="list-style-type: none"> - 350 x 160 x 570mm - 2.7 Kg - Touch Sensors (Head, Chin, Body, Legs) - Express various emotions 	 <p>GENIBO</p>	<ul style="list-style-type: none"> - 192 x 334 x 300mm - 1.6 Kg - Touch Sensors with camera and microphone - Emotional interactions through cute tricks
 <p>LION CUB</p>	<ul style="list-style-type: none"> - 250 x 190 x 190mm - 0.9 Kg - Sounds purr, mew and yow - Touch sensors with speaker 	 <p>WALL-E</p>	<ul style="list-style-type: none"> - 280 x 200 x 350mm - 2.5 Kg - Wireless remote control - Perform a special dance while playing music
 <p>Squawkers McCaw</p>	<ul style="list-style-type: none"> - 241 x 279 x 406mm - 1.8 Kg - Repeat words, sing and responds to touch - Can be taught to joke and song 	 <p>PLEO</p>	<ul style="list-style-type: none"> - 525 x 152 x 191mm - 1.6 Kg - Sensors for sight, sound and touch - 14 quiet motors for natural movements

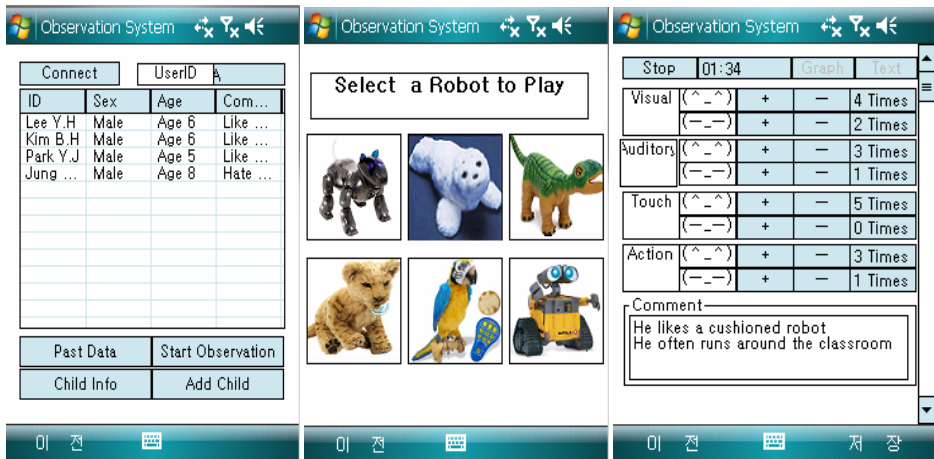
participated in each experiment, coping with the unpredictable behaviors of children with autism. The sequential order of the robot presentation for trials was PARO, Lion Cub, Squawkers McCaw, PLEO, GENIBO, and Wall-E. When a child was brought into the classroom, the therapist presented each robot system in the above order and observed the interaction process using the PDA device. At this moment, the therapist kept away from the children and did not deliberately intervene in interactions between the children and robots, except in emergency situations.

As mentioned in the previous section, the therapist observed the interaction process with efficiency and easiness. Although there were a lot of important factors in behavior monitoring, we adopted frequency and duration measurements to analyze the preferred degree of robotic systems or behavior patterns. This parameter is not only well suitable for qualitative data measurement, but also easy for transferring to digitalized information such as database systems. The actual monitoring interface of the PDA device is presented as section 3.3.

3.3 GUI (Graphical User Interface) Design

Generally, when the therapist writes down her observations using a traditional diary, it takes too much time to do her whole therapy duty. Thus, the design of a portable PDA device with a user-friendly interface was a critical issue to facilitate efficient observations. In order to reduce the input delay, we developed a touch screen based GUI, which provided easy insert, search, and store operations. Figure 3 shows the illustration of the proposed interface design. As shown, once the PDA is turned on, the therapist starts with the main page, which consisted of the following five buttons:

- **Insert a new child:** Insert a new child's information (e.g. name, age, gender, and unique descriptions) to the database
- **Modify child:** Modify the stored child information
- **Show past data:** Show the past play information with a statistical graph
- **Play start:** Start a new observation process with the robot selection page
- **Synchronization with server:** Fetch stored data entries from the remote server and show them



(a) Main page

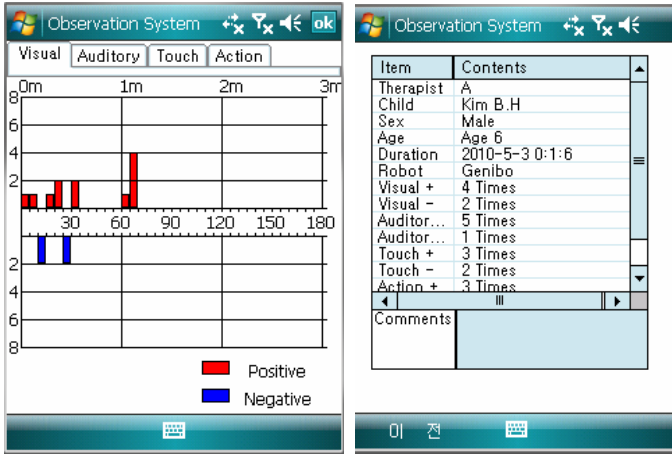
(b) Robot selection page

(c) Observation Input page

Fig. 3. GUI design of PDA

After finishing the child's input process, the therapist selected the target robot system for observation, which is shown in Figure 3-(a). Then, the therapist performed the input process using the observation input page shown in Figure 3-(b). The basic interaction criteria, for when the child approaches the robot and interacts with it, were visual, auditory, and touch. Whenever the therapist observed the preferred behavior and dispreference behavior for a certain sense, she touched the '+' and '-' button, respectively. For monitoring the duration of interactions, the observation input page of Figure 3 provides a timer, which is a toggle button to start and stop. The time gap between the start and stop buttons is the actual duration of the interactions. If there is another important description, the therapist may input using a free string text that is

similar to a traditional manual observation diary except that the PDA provides digital input mechanisms. All input information, including video data, was immediately transmitted to the remote server and synchronized according to the database schema, which is presented in Section 3.4. Although this GUI system provided an easy and efficient observation environment, the main observation activities, such as a judgment for preference and dispreference, belonged to the therapist since the proposed test-bed system was an assistance system, and not the all-in-one computer system that is beyond the scope of this paper.



(a) Graph page (b) Summary page

Fig. 4. Graph for data analysis

As shown in Figure 4, when the therapist wanted to review the past input data, the graph button can be used to provide a graph page for comparing preference and dispreference of frequencies, as well as a summarized table for all input information.

3.4 Database System for the Remote Server

The remote database server maintained whole information related to the robot assisted therapy process, including personal data about children and therapist in order to methodically analyze interaction patterns of children with autism by means of corresponding summary graph as shown in figure 4. In addition, this accumulated information may help therapists or parents to make a prescription for further treatments. Meanwhile, although the PDA device also has a local database system that provides fast data transactions, it cannot maintain the whole database including video and audio data; the PDA has limited storage capacity due to its hand held size. The main component of the proposed database system consists of eight tables, which are 'Information', 'Therapist_info', 'Child_info', 'Robot', 'Visual', 'Auditory', 'Touch' and 'Interaction' as shown in Figure 5. The Information table is the main schema that combines other tables using the index value; the corresponding data entries are shown in table 3.

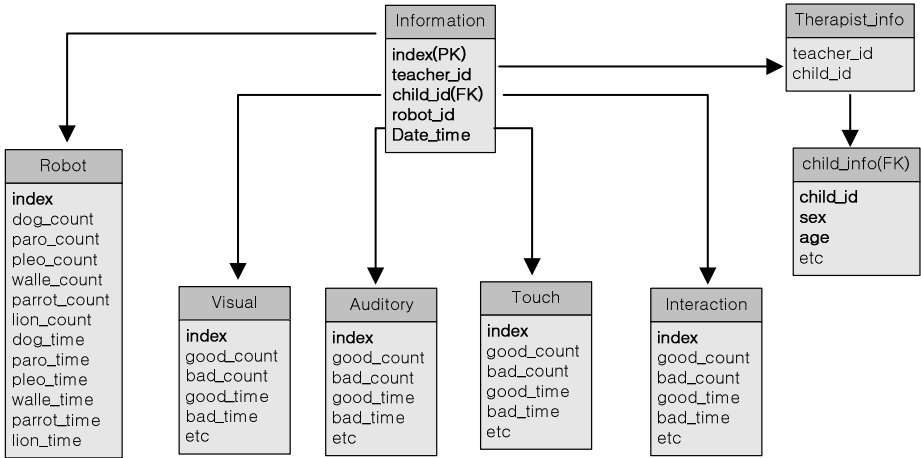


Fig. 5. Database Schema

Table 3. Attribute of Information table

index (INT Autoincrease NOT NULL)	As a primary key, it provides fast search operations It presents each experiment using autoincreasement
teacher_id (char(8) NOT NULL)	As a therapist ID, it provides search operation of the target child
child_id (char(8) NOT NULL)	As a child ID, it refers Child_info table and provides search operations
Robot_id (INT NOT NULL)	As a robot ID, it identifies each robot system
Date_time (datetime NOT NULL)	It maintains each experiment time

Table 4. Attribute for frequency and duration

good_count (INT)	Frequency of positive behaviors with a robot
Bad_count INT)	Frequency of negative behaviors with a robot
good_time varchar(80))	Duration of positive behaviors with a robot
bad_time varchar(80))	Duration of negative behaviors with a robot

Therapist_info and Child_info tables both contain personal information, of the therapist and the child respectively. For the preference information, of interactions between robots and children, three senses tables (Visual, Auditory and Touch) maintain data entries for frequency and duration as shown in Table 4.

4 Trial Results

We studied the interaction results through the proposed observation system according to the experiment scenarios mentioned in Section 3. The whole interactions were

recorded by PDA and transmitted to the remote server. After establishing the database, the server drew the average frequency and duration data graphs as shown in Figure 6-(a) and Figure 6-(b), respectively, as a function of trials. The duration value of Figure (b) was calculated by using the frequency value divided by the period of each trial. These results explained that the children were increasingly interested in the provided robot systems. Furthermore, there was no doubt that the proposed system provided not only fast information processing, but also easy data analysis for the therapist. In addition, to the best of our knowledge, our system is the first trial for efficient observations and is well suited to the requirements of the therapist, as mentioned in Section 1.

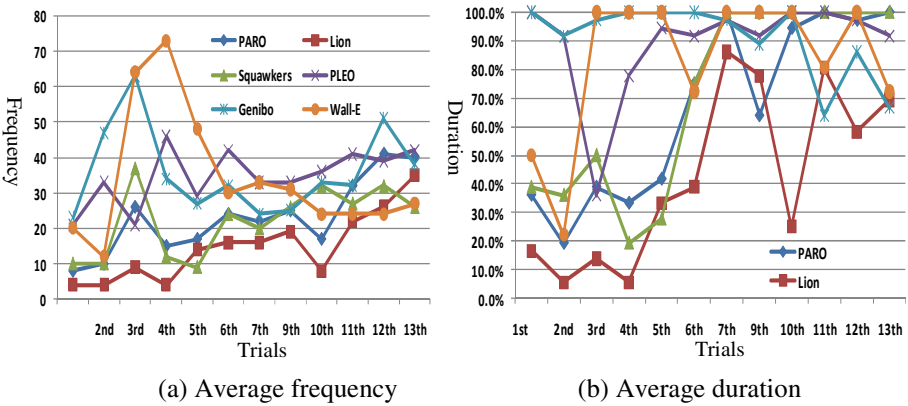


Fig. 6. Experiment graph drawn by the remote server

5 Conclusion

Robot technology with various digital devices is emerging for applications in therapy, rehabilitation, and the education of children with autism; robots are assumed social mediators. However, the therapist still has many difficulties in observing and analyzing the whole therapy processes with such robot systems. In this paper, we described the design architecture of our robot assisted observation system, which consisted of a GUI based input device, video cameras, a remote server, and several pet-type robots. First, one of the main functions of this system was to allow the therapist to easily describe the social interactions between children and the robots, using a mobile PDA device that provided input mechanisms for the children’s preferences according to behavioral frequency and duration. Second, the observed information, including personal data, was transmitted to the remote server, which maintained the database system for further analysis. Through the successful trial in the kindergarten, we show that our observation system is very useful for actual education environments.

In the future we need to improve our system to provide more intelligent data analyses such as medical diagnosis and behavior prediction with data mining. In addition, our system should express more criteria for social interaction activities, except for frequency and duration.

Acknowledgements

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Study on an Assistive Robot for Improving Imitation Skill of Children with Autism

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Abstract. In this paper, we report the effectiveness of a therapeutic humanoid robot for children with autism to improve his/her imitation skill. In order to realize this system, a robot has to provide two functions: mimicking and evaluating the child's motion in real time. The former function is achieved by selecting key frames using the Q-Learning approach to remove noisy camera data. The latter is established via a cluster-based framework on Mixture Gaussian and Expectation-Maximization algorithm using parameters which are converted by Principal Component Analysis. Practical experiments are shown in which autistic children interact with a robot and are trained by executing specific tasks for improving imitation skill.

Keywords: Children with autism, Human-robot interaction, Imitation skill, Robot mimicking, Motion planning, Humanoid robot.

1 Introduction

Many countries have social problems in which the number of the children with autism is increasing. Children with autism suffer from Autistic Spectrum Disorder in varying degrees typically leading to the following impaired social interactions: less ability to relate to other people; little usage of eye contact with other people; difficulties with verbal and non-verbal communication; and difficulty in understanding the intentions, feelings and mental states of other people [1].

There have been many studies to try to improve these disabilities. For example, Kozima *et al.* [3] developed Keepon, creature-like robot, which is designed to conduct non-verbal interactions with children in order to help them study, test and elaborate on psychological models of the development of social intelligence. Robin *et al.* [4] used robots as "interactive toys" which can facilitate and encourage interaction of children with autism. Michaud *et al.* [5] created Roball which can move by itself and discussed its functions of the child development.

Feil-Seifer and Mataric [6] proposed a control architecture of a supporting robot which interprets a child's activity and social behavior and produces an appropriate reaction behavior for the child. Our research group [7] put forward a system which autistic children get joint attention skill using a humanoid robot. By monitoring the child's gaze in real time, a supervised Mixture Gaussian-based cluster method was used to detect the child's intention to complete a goal-directed task smoothly.

Imitation is also important when the child's parents or teachers teach him/her something. Nadel *et al.* [8] discussed about innate imitation in babies and have shown that preverbal children use immediate imitation in their social exchanges. Additionally she and her colleagues [9] discussed about imitation in autonomous robots and showed how a robot can perform spontaneous imitation.

However, taking real time communication with autistic children for improving imitation skill into account, it is important for a robot to highlight not only correct parts of their imitation but also how to modify any mistaken motion. To do this a robot system which can evaluate a child's motion by comparing sample (instructor's) motion with these of the child. Then we show that our humanoid robot has the potential for improving imitation skills of autistic children.

2 Imitation-Based Interactive Scenario

2.1 Imitation-Based Interactive Scenario

Fig. 1 shows the proposed scenario for improving imitation skill for autistic children. The key points of this scenario are as follows: A robot attracts a child's attention. A robot teaches the child the assignment motion and gives feedbacks about child's motion. For example, if the child moves correctly, a robot gives a compliment to him/her for raising his/her motivation of doing these tasks. Whereas, if the child moves incorrectly, a robot shows not only correct motion but also how he/she made mistakes, because comparing two motions makes easier to understand than teaching only a correct motion. A child's teacher encourages the child and shares his/her pleasure when he/she can do tasks correctly.

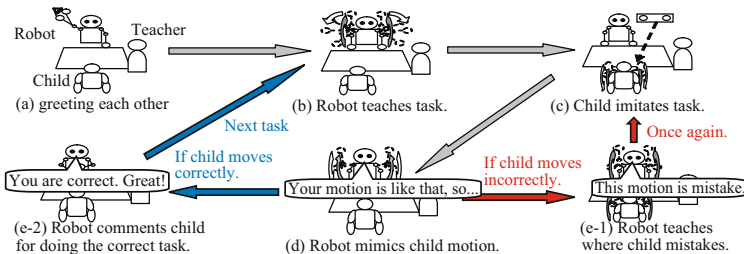


Fig. 1. Imitation-based interactive scenario

There are many studies for a robot which has mimicking skill using motion capture system [10] or image processing techniques [11]. In those studies, sensors have to be placed on human body, so autistic children may cause his/her discomfort when sensors are put on child's body. To solve these problems, we select a special shirt as shown in Fig. 3(a) in which the differential colors are set at the positions where we want to measure the motion instead of sensors.

2.2 Functions for the Scenario Realization

Fig. 2 shows a Child-Robot interaction system based on interactive scenario. A robot does a real time interaction with a child, because long time interval between child movements and robot indications makes difficult for teachers to teach something him/her due to child's low concentration. The detail of these methods shown in Fig. 2 is described in the following section.

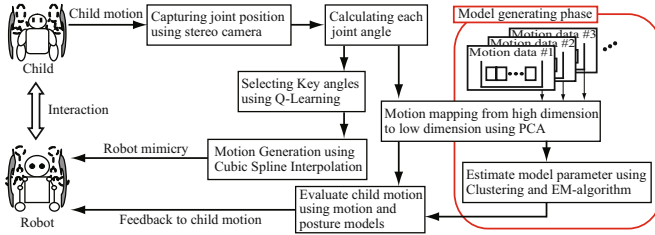


Fig. 2. Child-Robot interaction system for evaluating and correcting each motion

3 Method for Mimicking and Evaluating Child's Motion

Since the camera system has to calculate the enormous visual data of child motion, the amount of data is reduced appropriately for real time interaction.

3.1 Calculation of Child's Joint Angles

We show how to calculate joint angles which determine the child's posture. The target joint angles are as follows: head front angle, neck twist angle, neck tilt angle, hip front angle, shoulder front/rear angle, shoulder right/left angle, shoulder twist angle, elbow angle. A child wears a particular shirt. 12 joint angles of child's upper body shown in Fig. 3(b) are converted from his/her 8 joint positions shown in Fig. 3(a) measured by one stereo camera. To locate joint positions, the different colors are set on cephalic part, abdominal part and joints of shoulder, elbow and wrist. The stereo camera system used in this study can measure the center position of the specified color area. Since noise factors, such as a shadow and environmental influence, may interrupt measuring correct positions, these are cleared up using the method described the following section.

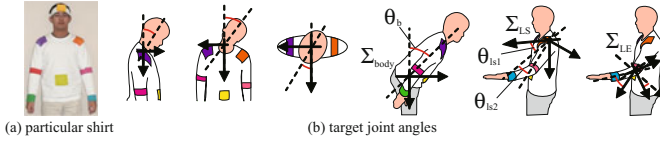


Fig. 3. Particular shirt which is used calculating target joint angles

The procedure of obtaining joint angles from stereo camera data are follows: Here, relative coordinate systems of body Σ_{body} , left shoulder Σ_{LS} and left elbow Σ_{LE} are defined as shown in Fig. 3(b). Position vector $\mathbf{p}_{ls} = [p_{lsx} \ p_{lsy} \ p_{lsz}]^T$ in Σ_{LS} is calculated from the combination of $\mathbf{p}_b = [p_{bx} \ p_{by} \ p_{bz}]^T$ in Σ_{body} and hip front angle θ_b shown in the following equation:

$$\begin{bmatrix} p_{lsx} \\ p_{lsy} \\ p_{lsz} \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(-\theta_b) & \sin(-\theta_b) & 0 \\ 0 & -\sin(-\theta_b) & \cos(-\theta_b) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -p_{lsx} \\ 0 & 1 & 0 & -p_{lsy} \\ 0 & 0 & 1 & -p_{lsz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_{bx} \\ p_{by} \\ p_{bz} \\ 1 \end{bmatrix}. \quad (1)$$

Equation (1) shows in the following equation:

$$\begin{bmatrix} \mathbf{p}_{ls} \\ 1 \end{bmatrix} = \begin{bmatrix} {}^{ls}\mathbf{R}_b(\theta_b) & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{I} & {}^{ls}\mathbf{q}_b \\ \mathbf{0} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{p}_b \\ 1 \end{bmatrix}. \quad (2)$$

where ${}^{ls}\mathbf{R}_b(\theta_b)$ is the rotation matrix and ${}^{ls}\mathbf{q}_b$ is the translation matrix. Using measured position of $\mathbf{p}_{le} = [p_{lex} \ p_{ley} \ p_{lez}]^T$ in the coordinate system Σ_{LS} , left shoulder front/rear angle θ_{ls1} , shoulder right/left angle θ_{ls2} are calculated by the following equations:

$$\theta_{ls1} = \frac{p_{ley}}{p_{lez}}. \quad (3)$$

$$\theta_{ls2} = \frac{-\sin(\theta_{ls1})p_{ley} + \cos(\theta_{ls1})p_{lez}}{p_{lex}}. \quad (4)$$

All the angles are calculated in the same way, θ_j^i , where $i = 1, 2, \dots, N$ is the frame number and $j = 1, 2, \dots, 12$ is the joint number, are calculated. These are used in the next process described in the following section.

3.2 Mimicking a Human Motion

Robot motion for mimicking child’s motion is calculated using human joint angles θ_j^i . The key frames are used for making robot motion because data processing time is large and significant noise may overlapped with signal. In this study, frames which have large angular velocities or accelerations are extracted as key

frames. The procedure of extracting key frames is as follows: The correlation value γ_i represents variation of motion:

$$\gamma_i = \left[\sum_{j=1}^{12} (\theta_j^i - \bar{\theta}^i) (\theta_j^{i+1} - \bar{\theta}^{i+1}) \right] / \left[\sqrt{\sum_{j=1}^{12} (\theta_j^i - \bar{\theta}^i)^2} \sqrt{\sum_{j=1}^{12} (\theta_j^{i+1} - \bar{\theta}^{i+1})^2} \right], \tag{5}$$

where

$$\bar{\theta}^i = \frac{1}{12} \sum_{j=1}^{12} \theta_j^i. \tag{6}$$

γ_i takes a range: $-1 \leq \gamma_i \leq 1$. If γ_i is nearly 1, the change of motion is little, if γ_i is nearly -1 adversely, the change is large. So, at first, frames whose γ_i is low included in 10 percent of all the frames are selected as candidate frames because these frames have great changes of angular velocities or accelerations. However, γ_i is also low when significant noise are overlapped. For extracting appropriate key frames, Q-Learning is applied in order to take away the frame with significant noises. After Q-Learning is applied, for making smooth robot motion using key frames, cubic spline interpolation are applied using the joint angles of key frames.

In order to confirm the effectiveness of our method, we conducted an experiment. The experiment is that a person raises right hand in the first step, then drops right hand and raises his left hand in the next step, and drops left hand and raises right hand in the last step as shown in the upper row of Fig. 4(a). The motion obtained by the robot mimicking human motion is shown in the lower row of Fig. 4(a) and the trajectories of human and a robot joint angle of shoulder front/rear and right elbow are shown in Fig. 4(b)-(d). The result shows that a robot mimics human mo-

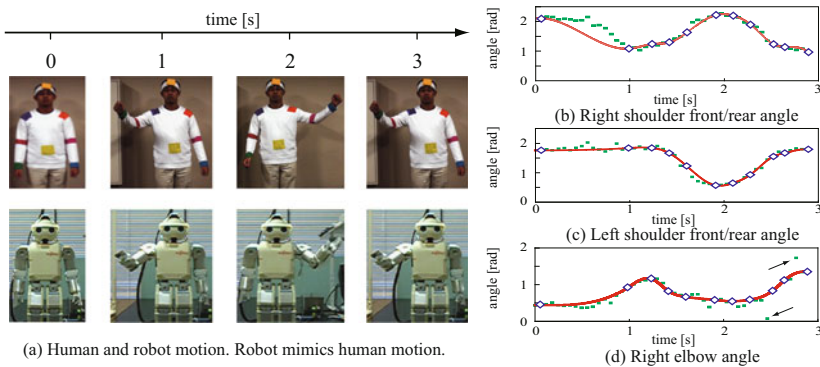


Fig. 4. Robot mimicked result. Person moves as shown in (a), a robot mimics human motion. Transitions of joint angles of human and a robot are shown in (b)-(d). In (b)-(d), red curve is the trajectory of joint angle of robot motion, green dot (●) is the joint angle of human posture in each frame, blue diamond (◇) is the joint angle of key frame. Trajectory of robot motion passes the posture of key frames.

tion appropriately and smoothly. But in Fig. 4(b), trajectory of human and a robot did not correspond in the first step because there are little key frames in the time. However, although in Fig. 4(d), significant noises are observed at between 2.5 and 2.8 s (which black arrow points at), trajectories of the robot angle are not intervened by these noises because selecting key frames are appropriate. If Q-Learning is not used, the frame with significant noise data was selected as a key frame in that time because the value of γ_i was low.

3.3 Evaluating the Human Motion

In this section, we describe the method that a robot feedbacks the child motion. Conventional methods for evaluating a human motion needs a sample motion to compare with actual human motion. For example, Yang *et al.* [13] proposed a method for recognizing of whole-body gestures using hidden Markov models(HMMs). However, this method can not detect what part of the motion is mistaken. In the proposed interactive scenario shown in Fig. 1, a robot has to teach what part of the motion is mistaken, so we propose the following method which consists of three steps.

In the first step, the calculated joint angles $\theta^i = [\theta_1^i \ \theta_2^i \ \theta_3^i \ \dots \ \theta_{12}^i]^T \in R^{12}$, where i is the frame number, are converted to the low-dimensional parameters using Principal Component Analysis (PCA). The a -th component vector n_a and eigen value σ_a are calculated using PCA. The minimum number of component m is determined using cumulative contribution ratio P_m as

$$P_m = \left(\sum_{a=1}^m \sigma_a \right) / \left(\sum_{b=1}^{12} \sigma_b \right) > 0.8, \tag{7}$$

where

$$m = \arg \min_m P_m. \tag{8}$$

The posture vector at the frame i in the latent space: $x^i \in R^m$ is calculated using a conversion matrix $A = [n_1 \ n_2 \ \dots \ n_m]^T \in R^{m \times 12}$ as following equation:

$$x^i = A\theta^i. \tag{9}$$

As a result, x^i ($i = 1, 2, \dots, N$) are calculated.

In the second step, cluster analysis is applied to x^i and the number of clusters is decided using agglomerative clustering algorithm and Expectation-Maximization(EM) algorithm [12]. We assume that each subclass has multivariate Gaussian distribution, the probability density function is:

$$p_t(x_n^i | \lambda) = \sum_{k=1}^K \frac{\Pi_k}{(2\pi)^{m/2}} R_k^{-\frac{1}{2}} \exp \left[-\frac{1}{2} (x_n^i - \mu_k)^T R_k^{-1} (x_n^i - \mu_k) \right]. \tag{10}$$

where λ is cluster parameter, K is the number of subclasses, Π_k is mixture ratio, μ_k is average, R_k is covariance matrix, respectively. In order to decide the number of clusters, we conduct the following procedure: In the initial state, N clusters which include only one x^i are created respectively. Then the pair of clusters which are placed at a short distance is merged repeatedly until the number of cluster becomes 1. When the pair of clusters is merged, the Minimum Description Length (MDL) is calculated.

$$\text{MDL} = - \sum_{i=1}^N \log[p(x_n^i)] + \frac{1}{2}L \log[Nm]. \quad (11)$$

where

$$L = K \left[1 + m + \frac{(m+1)m}{2} \right] - 1. \quad (12)$$

We select the number of clusters, for which the value of MDL is minimum among the numbers for the above procedures.

In the third step which is the experimental step, a stereo camera monitors human motion, then x^i are calculated using equation (9). Next, $p_t(x_n^i|\lambda)$ are calculated using equation (10). And the log likelihood in the following equation is calculated:

$$t_{max} = \arg \max_t \sum_{n=1}^m \log[p_t(x_n^i)]. \quad (13)$$

To Substitute each model data of task into equation (13), if t_{max} of one model task is larger than ones of the other tasks, the camera system judges that the person is doing this task. This system can evaluate that the person does task correctly comparing the task of computing above method and the one we set.

Two models are defined: a motion model which shows what kind of motion the person acts, a posture model which shows what stage of the motion, for example, initial state, middle state and end state. Two models are important to evaluate human motion because we should judge that it is a mistake when specified motion follows the inverse trajectory.

For evaluating this method, we conduct an experiment. We set the sample motion which consists of the following two subtasks as shown in Fig. 5(a): **1**) A person raises both hands, and then **2**) drops both hands. In the experiment, a subject acts correctly the subtask **1**, but consciously acts in moving the subtask **2** incorrectly. The experimental result is shown in Fig. 5(b)-(d). Fig. 5(b)-(c) shows the calculation result of t_{max} about tasks(raise/drop hands) and postures(initial/middle/end state). Fig. 5(d) shows that larger task and posture are selected as judged result. The result shows that this system judges that a person acts subtask **1** correctly, but also judges that a person acts subtask **2** incorrectly. So this system can judge appropriately. The calculation time for evaluating a human motion is about 0.0037 s per frame on an average, so this system can conduct the experiment in real time.

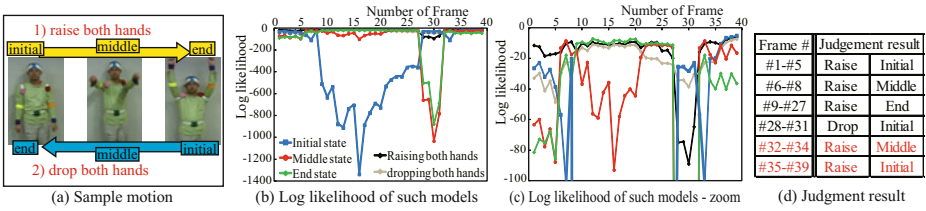


Fig. 5. Experimental result. (a) is sample motion. (b)-(c) are log likelihood of such models. (d) is the judgment result what is the task and what state in the task.

4 Experiment for Improving Child Imitating Skill

We show the effectiveness of our method by the experiment which autistic children participate using the system in section 3. The experiment environment is shown in Fig. 6. As shown in Fig. 6(a), we used children’s classroom as location for the experiment because the children are familiar with it. In order to eliminate a environmental factor, the experimental space is surrounded by walls and curtains. A child can not see a person except for his/her teachers. A child sits down on a chair across the table from a humanoid robot(HOAP-3, FUJITSU AUTOMATION LIMITED) like Fig. 6(b). His/her teachers who prompt their motivation sit the next to child. The child wears a shirt with seven colors and he/she is monitored by a stereo vision camera(Bumblebee 2, Point Grey Research, Inc.). Because the child will dislike wearing a head marker which is shown in Fig. 3(a), a head marker was not used. It means the parameter of $\theta^i \in R^4$ in equation (9) was missed. He/she weared the shirt a week before the experiment in order not to feel discomfort by wearing the shirt. An additional video camera monitors the child in order to analyze the behavior of the child after the experiment. The each experiment took about 5 minutes and 3 boys and 1 girl participated the experiment. Some of them had participated the previous experiments for enhancing the joint attention reported in 7. We prepared three tasks: raising and dropping right hand, left hand and both hands. A robot

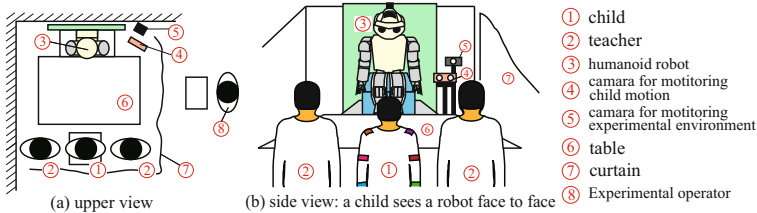


Fig. 6. Experimental environment: In order to keep child’s concentrate, child can not see person except for his/her teachers. Operator sees the monitor and has a role of emergency stop of this system for the child safety.



(a) Initial state: Child does not raise hand.



(b) Middle state: Child is raising hand.



(c) End state: Child have raised hand.

Fig. 7. Experimental scene: A child puts up his left hand

teaches, mimics and evaluates the child motion automatically. An experimental operator conducts experiment by changing tasks or finishing the experiment by taking the child mental condition into account.

This experiment was carried out for two days in order to evaluate the child's ability to adapt the experiment. In the experiment, the robot and his/her teachers encouraged him/her to conduct the specified task. Fig. 7 shows the circumstance of a child raises left hand. In this figure, the stereo camera system evaluated that his motion was correct. The stereo camera system evaluated appropriately in the cases of other tasks. Children sometimes did a task voluntarily, but sometimes did by a teachers' encouragement. A robot also could mimics child motion.



(a) Robot moves as greeting



(b) The scene of raising both hand



(c) The scene of saying good-bye

Fig. 8. Experimental scene. A child seems to enjoy doing the specified task.

Experiments with 4 subjects were conducted for two days and we discussed with their teachers about the effectiveness of our method after the experiments. There were children who can interact with robot, on the other hand, there were also children who cannot interact with robot. However, teacher's evaluation shows that the experiments of the second time is better than the first experiment, which indicates the possibilities of improving child's capability of the imitation. Characteristics of each children have to be considered to determine the subjects of the training. For example, one child do not like a long-sleeved shirt, an other child likes shining of robot eyes. Fig. 8 shows the other experimental scene. Note that child's eyes are hidden by black bar because of privacy concerning. But he/she seems to enjoy communicating with robot.

5 Conclusion

In this study, we have proposed methods for mimicking and evaluating human motion. The former function is realized to select key frames using Q-Learning

approach for removing the noisy camera data. The latter function is realized to use a cluster-based framework on Mixture Gaussian and Expectation-Maximization algorithm using parameters which are converted by Principal Component Analysis.

We conducted experiments in which children interacted with a robot through imitating robot's motion.

The result shows that a humanoid robot has a potential of the effective tool for interacting with autistic children and improving their imitation skill. As for future subject, since there are large differences of child characteristics, the program of training has to be made on a personal basis which each child can have interests.

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Developing Play Scenarios for Tactile Interaction with a Humanoid Robot: A Case Study Exploration with Children with Autism

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Abstract. The work presented in this paper is part of our investigation in the ROBOSKIN project¹. The paper presents the completion of the first phase towards skin-based robot assisted play that included a literature review, exploratory studies and building play scenarios. The review highlights aspects of the social and the sensory impairments of children with autism, and provides the background knowledge and context for developing tactile human-robot play scenarios that are appropriate to this specific user group. The paper reports on higher-level user requirements for skin based interaction for these children alongside their exploratory studies with the humanoid robot KASPAR. This is followed by the presentation of an initial play scenario that is based on turn taking and imitation games, together with the related educational and therapeutic objectives relevant for children with autism.

Keywords: Robot Assisted Play, Assistive Technology, Human-Robot Interaction, Autism Therapy.

1 Introduction

Touch is known to be a key element in child development. From birth, the need for maternal contact² is evident amongst humans and non-human primates alike. Various studies have shown that skin-to-skin contact of mothers with their newborn babies has a long lasting effect in later stages of life on the children's intelligence and comprehension. Bowlby asserts that attachment is the basis for healthy human development [1]. Ibraimov further illustrates how the sensitivity of our skin receptors informs us of our internal and external environment [2]. The sensorimotor stage, in Piaget's theory of development, is the first stage that initiates the healthy development of an individual. It is this stage in which children use their senses to learn about the environment. Touch is regarded as the first modality to be developed and is suggested to be the most prominent exploratory sense at this stage [3]. Touch deprivation in early stages, can lead to speech retardation, learning disabilities as well as emotional problems in later life [4-6].

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² Which may be a consistent caregiver other than the mother.

In recent years an increasing number of research studies have shown the potential use of robots as tools to support the development of different skills in children with special needs. The AuRoRa project [7] reported how mobile robots and humanoid robots can be used to mediate interactions between children with autism and peers and adults [8-10]. Other robots have been used by various researchers to engage autistic children in playful interactions, e.g. artificial pets such as the baby seal *Paro* and the teddy bear *Huggable* [11, 12], and the small cartoon-like *Keepon* [13], to mention just a few.

1.1 Touch, Play, and Child Development

It is widely accepted that play has a crucial role in a child's development. The World Health Organisation in its ICF-CY (International Classification of Functioning and Disabilities, version for Children and Youth) publication considered play as one of the most important aspects of a child's life to be considered when assessing children's quality of life [14]. During play children can learn about themselves and their environments as well as develop cognitive, social and perceptual skills [15]. Literature suggests that play is an essential activity during childhood, and that its absence provides an obstacle to the development of a healthy child possibly leading to general impairment in their learning potential, cognitive development, and may result in isolation from the social environment [16-18].

Physical touch is one of the most basic forms of communication. Tactile sensing can help to provide awareness of one's own self and each other. In the playground, touch and physical contact are used by children to communicate, to build trust, to give or receive support and to develop their social relationships. In therapy, the tactile sense can be used individually to increase self knowledge, body image, to achieve sense of stability, and build confidence. Touch of another person when it happened is seen also as a way of breaking through isolation. It has a social element, a sense of community that positively affirm the patients [19], [20].

1.2 Autism and Tactile Interaction

Autism here refers to Autistic Spectrum Disorders, a range of manifestations of a developmental disorder characterized by impairments in communication, social interaction, and imagination and fantasy [21] that can occur to different degrees and in a variety of forms [22]. People with autism often experience an inability to relate to other people, show little use of eye contact, difficulty in verbal and non-verbal communication, and tendencies toward repetitive behaviour patterns [23].

Some people with autism have hyper-sensitive sensory conditions [24]. Some might be hyposensitive and seem not to feel pain or temperature. In day-to-day interaction, people with hypotactility may not feel or notice touch unless it is very firm or intense. As a result they might be slow to response to others who might use touch to gain their attention [25]. Their touch of other people or objects would not be sensed appropriately and unintentionally they could hurt other people, or break objects. Other people with autism might have a hypertactility condition which is very common [26] and results in overwhelming sensation. As touch can be excruciating people with this condition fear being touched. This fear could be so great, it can send them into a panic attack [24]. A dysfunctional tactile system may lead to self-imposed isolation.

On the other hand tactile interaction (if tolerated) might be an important means of communication for children with autism. As stated by the American National Institute of Mental Health [27], some children diagnosed with autistic spectrum disorder remain mute throughout their life, and other children typically use their verbal skills inadequately. Caldwell suggests that problems with verbal skills and eye gaze in children with autism create the need for touch to replace these detrimental ways of communicating [28].

We argue that a 'tactile' robot can be used at a basic level as an extension of the therapist or another person, or a buffer that mediates by providing indirect rather than direct human-human contact, until such time that the person builds enough strength and confidence to tolerate direct human contact.

The nature of touch is very individual to a person and so a robot with tactile applications can take into account individual needs and differences and could adjust its behaviour accordingly. It also could allow a person with autism to explore touch in a way that could be completely under their control.

1.3 Social Learning and Imitation, and the Case of Autism

Social learning and imitation play a significant role in the development of social cognition. Imitation can serve not only as a learning tool to acquire new physical skills but also provides the foundation for learning about the social world that surrounds us [8, 29]. From birth, imitation plays a critical role in the development of social cognition and communication skills, helping an infant in forging links with other people [29]. Imitation and turn taking games are used in therapy to promote better body awareness and sense of self, creativity, leadership and the taking of initiative both in children and adults (as used in Dance Movement Psychotherapy by [30, 31]). Nadel explored the use of imitation as a communicative means in infant with autism [29] and found significant correlation between imitation and positive social behaviour. It was also found that autistic children improve their social responsiveness when they are being imitated [29, 32, 33] In therapy too, imitation, reflection and synchronous movement have been used with autistic children to develop social interactions [20, 34].

Tactile play scenarios for child robot interaction that will include turn-taking and imitation games could facilitate the above therapeutic objectives and may improve social responsiveness of children with autism. Note, while we have been using KASPAR for our work with children with autism for a few years, the new project FP7 European project ROBOSKIN focuses specifically on the use of tactile sensors to support tactile human-robot interaction. Thus, the work presented in this paper goes beyond any of our previously published articles.

2 Developing Tactile Play Scenarios

Scenarios here are seen as higher-level conceptualisations of the "use of the robot in a particular context". In the current work, scenarios are being developed specifically for *skin-based interaction* for robot assisted play targeting children with autism. A design process and a unified structure of the scenarios were adopted and modified from the scenario-based design methodology [35, 36] and from results of the previous FP6 project IROMECA [37, 38]. This structure consists of the description of actors and

their roles, the type of play, the description of the activity, the recursive model, the place and setting, the artifact used, and the duration of the activity. The design process (see Fig 1) is based on User Centered Design principles and it involves the users (primary and secondary users) in every stage of this process. It includes ongoing exploratory field trials with the target user group (in this case children with autism) together with continued consultation with experts (teachers and therapists who know the children) in order to feed back into the design loop³.

The play scenarios are being developed against specific therapeutic and educational objectives in line with relevant child developmental areas that include sensory development, communicational and interaction, cognitive development, social and emotional development and motor development. These objectives were identified previously in consultation with professionals (e.g teachers, therapists) during user panel meetings and have been classified with reference to the ICF-CY, the International Classification of Functioning – version for Children and Youth [14, 39].

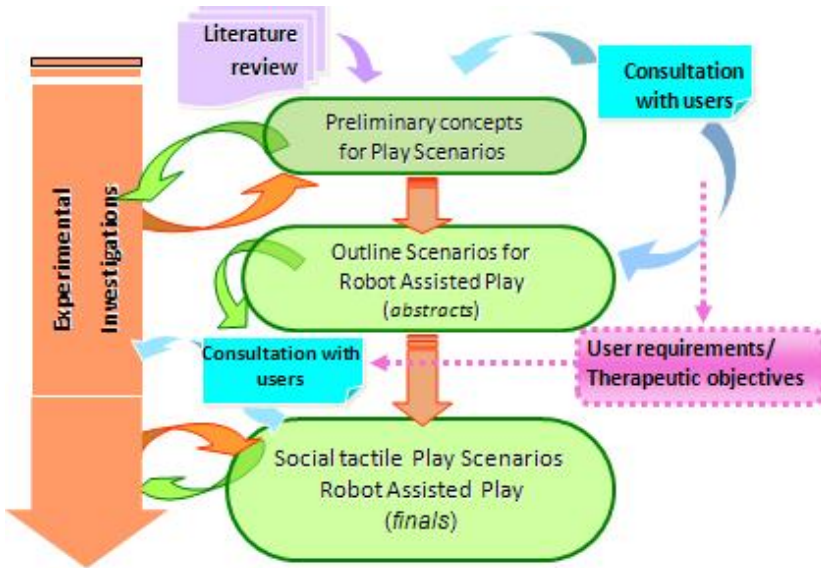


Fig. 1. Developmental process of scenarios for skin-based robot assisted play

2.1 Exploratory Field Trials

As stated above, building tactile play scenarios to be used by children with autism requires ongoing exploratory field trials together with continued consultation with the people who know the children in order to feed back into the design loop. This is due to the nature of this user group which includes children with a wide range of abilities and variety of expected behaviours (unpredictable at times).

³ The design process in Fig 1 is based on [38] where a further detailed description of the whole developmental process of play scenarios can be found.

First, a high level requirements analysis for skin based interaction for these children was conducted, based on initial video analysis of children with autism interacting with the robot KASPAR. KASPAR is a child-sized humanoid robot that was developed at the University of Hertfordshire which acts as a platform for Human-Robot-Interaction studies [40]. This initial analysis identified typical and frequently occurring touch interactions that are very relevant in this application domain. Three main types of touch, when children use their hands to touch the robot, could be identified: grasping, stroking and poking. The intensity of touch varied between tight or firm and very light or ‘gentle’ (see examples in Fig 1 below). The full analysis can be found in [41].



Fig. 2. Typical type of tactile interaction: (left to right) gentle stroke, tight grasp, gentle grasp, firm press

Further research is necessary, however, this first analysis highlights the type of touch that needs to be detected and provides preliminary requirements for a) the development of new skin technology, as one of the key objectives of the project RoboSKIN, and b) algorithms for the identification of these types of child-robot tactile interactions, and c) for the development of tactile play scenarios.

To help us build appropriate social tactile play scenarios a series of experimental investigations were conducted with children with autism. Two different exploratory user studies in two schools with two KASPAR robot platforms took place. One study, which involved 14 children with autism, was designed to provide essential observational data on children’s behaviour during child-robot tactile interaction. The other study conducted preliminary investigations to further explore sensor positioning and sensory readings during interaction of the robot with four children with autism. KASPAR was equipped with tactile sensor prototypes to try to capture the temporal and spatial characteristics of any tactile interactions that may occur. A full description of this study can be found in [42]. During this study, initial tactile imitation and turn-taking games were explored (see Fig 3). This provided input for developing the tactile play scenario described in section 2.2.



Fig. 3. Exploration of a tactile imitation game

2.2 Tactile Play Scenario and Its Educational and Therapeutic Objectives

The following initial exploratory play scenario is based on turn taking and imitation game and was developed alongside the initial exploratory studies. The Sub-headings (*italic letters*) below represent the identified building blocks of the unified structure of play scenarios. Further play scenarios will be developed during the next phase of field trials.

TITLE: Imitation game with a humanoid robot – KASPAR

ACTORS/ROLES

The actors of the scenarios are one child and one adult or two children. The adult can be a parent, a teacher, a therapist, etc. The child operates the robot and initiates new movements and postures, whilst the second player imitates the robot.

ACTIVITY DESCRIPTION

The child is shown how to operate the robot by touch. Touching different parts of the robot will cause different movements, e.g. touching the hand will cause the robot to raise its hand. Touching the shoulder will cause the robot to move the arm to the side etc. The robot is able to classify different types of touch and depending on whether a child touches the robot e.g. in a gentle or rough manner the robot will respond with appropriate audio/visual feedback (e.g. sound and facial expressions such as a smile for a gentle touch and a frown as a response to a rough touch).

The game starts with the child operating the robot by touching it in different locations, changing the robot's posture and making it move (e.g. the arm or head). The other player is imitating the robot, moving their arms and head in the same way and imitating the robot's facial expressions.

This can be repeated many times going through the repertoire of all the robot's postures, expressions and movements several times.

ACTIVITY MODEL

The robot has 9 behaviours movements/postures:

- Moving each arm individually up or down;
- Moving each arm to the side.
- Moving the head to each of the sides individually.
- Moving the head repeatedly from side to side (as saying 'no')
- Shaking the head up & down (as saying 'yes')
- 'Happy' posture - arms open to the side – head and eyes straight forward, mouth open with a smile

A different facial expression is associated to each movement (e.g. eyes open or closed or eyes following the direction of the pointing, head could tilt to any direction, the mouth could provide varied expression ('happy'⁴/smile or 'sad'), eyes could blink.

⁴ Note, we are using terms such as 'happy', 'sad' etc. in terms of how typically developing human interaction partners perceive the robot's expressions from an interactive perspective – these expressions are not based on detailed models of emotions or facial expressions as they are studied in the literature.

The interaction here is between the child and the other player (adult or another child), under the child’s control. The child, in controlling the robot’s postures, causes the other player to change his/her posture in response. The child then checks the response to see if the imitation was ‘correct’ (in the child’s view).

The players take turns and change roles of who is controlling the robot and who is imitating. The adult, when in control, gives a positive feedback to a correct imitation performed by the child.

PLACE/SETTING

The robot is placed on a table. The adult sits next to it. The child is sitting in front of the robot.

ARTIFACTS/MEDIA

KASPAR is a child-sized humanoid robot. It has 8 degrees of freedom in the head and neck and 6 in the arms and hands. The face is a silicon-rubber mask, which is supported on an aluminium frame. It has 2 DOF eyes fitted with video cameras, and a mouth capable of opening, smiling and blinking. Details of the robot are provided in [40].

TIME/FLOW

The duration of this activity can be from under a minute to 15 minutes or even longer, depending on how long the child is interested and engaged in the game.

KEYWORDS

Enjoyment, excitement, taking initiative, turn-taking and imitation- social interaction with another person.

EDUCATIONAL and THERAPEUTIC OBJECTIVES	
⊕	<p>Global intellectual functions</p> <ul style="list-style-type: none"> • to improve understanding of cause and effect
◆	<p>Perceptual functions</p> <ul style="list-style-type: none"> • to improve proprioception
◆	<p>Experience of self</p> <ul style="list-style-type: none"> • to improve the sense of self and the awareness of one's own body and identity
◆	<p>Psychomotor functions</p> <ul style="list-style-type: none"> • to improve psychomotor control • to improve organization of psychomotor functions
◆	<p>Copying</p> <ul style="list-style-type: none"> • to improve the ability to mirror and imitate simple and complex movements
⊕	<p>Attention</p> <ul style="list-style-type: none"> • to improve focusing attention • to improve the maintaining of attention
◆	

EDUCATIONAL and THERAPEUTIC OBJECTIVES	
⊕	<ul style="list-style-type: none"> • to improve shifting attention
◆	<ul style="list-style-type: none"> • to improve joint attention
⊕	<p>Mobility (body)</p> <ul style="list-style-type: none"> • to increase gross motor control
◆	<p>Basic interpersonal interaction</p> <ul style="list-style-type: none"> • to improve turn taking • to improve gaze shift • to increase eye contact with others • to improve level of response to others
◆	
◆	
◆	
⊕	<p>Particular interpersonal relationships</p> <ul style="list-style-type: none"> • to encourage participation with classmates, to enjoy shared activities
⊕	<p>Engagement in play</p> <ul style="list-style-type: none"> • to foster shared cooperative play

Legend:

◆ Main objective; ⊕ Secondary objective

3 Conclusion and Future Work

This paper reported on the completion of the first phase towards skin-based robot assisted play for children with autism that included a literature review, exploratory studies and building play scenarios. The literature review provides the background knowledge and context for developing tactile play scenarios that are appropriate to the specific user group. Understanding the social and the sensory impairments of children with autism and its potential effect on their behavior provide the inspiration for developing tactile social play scenarios against specific therapeutic objectives. The paper reports on the exploratory studies with the humanoid robot KASPAR that was equipped with temporary tactile sensing capabilities and presents the first completed play scenario that was developed based on tactile imitation and turn-taking game, together with its therapeutic and educational objectives. Further social tactile play scenarios will be developed in the next phase of the project along side continued user trials, when it is planned that the robot will be equipped with ROBOSKIN based technology, and semi autonomous robot behavior will be developed. This will facilitate the development of more complex play scenario further addressing the special needs of children with autism. Further long-term studies will be required in order to evaluate the positive effect that this technology might have on the children as a result of robot assisted play.

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Development of PARO Interventions for Dementia Patients in Dutch Psycho-geriatric Care

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Abstract. Social Robots are believed to have great potential for long term care. The uptake of Social Robots in daily care provision will depend on demonstrated added value of such systems in practice. To assess the added value, the availability of a technical system as such is insufficient. Interventions need to be defined describing the goal, target group, environment and how care staff should act to pursue effective application of a robot system. For the seal robot Paro three such interventions have been developed in collaboration with psycho-geriatric care professionals. The interventions provide information on the aims of PARO application in daily care for psycho-geriatric patients and describe concrete outcomes to monitor the added value of robot interventions. The developed interventions also outline the application of PARO in care for a subsequent randomized clinical trial (RCT).

Keywords: Socially assistive robots, Paro, Dementia, Care interventions. Psycho-geriatric care.

1 Introduction

The ongoing development of technology provides a vast potential of opportunities for the provision of care in industrialized countries. On the basis of technologies such as ICT and robotics, applications are feasible to facilitate independence for elderly clients with disability or chronic conditions who receive regular care services. Moreover, professionals and informal caregivers could also be supported in their work by innovative technology. In the case of robotics, technology may support the execution of physically demanding tasks, by offering force exertion, repetitive task execution and/or high precision manipulation. Despite efforts for more than two decades, this potential has, so far, not been translated into successful applications for the domain of long term care, with some exceptions [1]. As explanation for this, technical barriers in terms of system reliability, robustness and intrinsic safety can be mentioned.

More recently the use of robot abilities has led to a fast-developing alternative application type; social robots. Social robots do not exert significant forces to the human body and may not even be required to make physical contact with users for their functioning. Multimodal interfacing mimics social interaction between human and robot, potentially offering support at a psycho-social level in long term care. For such applications, system robustness, reliability and intrinsic safety are easier to achieve than the more physical types of care robots, thus paving the way to application of robots in daily care. However, for the successful application of any type of robot technology in care, the availability of a sound technical system by itself is not sufficient. The uptake of a robot requires embedding in a care intervention. Such intervention defines the use of the robot for its target population(s) in care provision. Moreover, the intention of the intervention should be specified and the intended effects, or the expected added value from use of the system, should be clarified. Finally, information and/or instructions for both care receivers and providers must be available. In all, the intervention must convince (public) care financiers to reimburse the application of robot interventions within the healthcare system. Without the context of an intervention it is most likely that the application of the robot in care will be seen as an entertaining gadget only.

Within the more specific domain of socially assistive robotics (SAR) 23 systems have become available in recent years [2]. A literature review revealed that little is known about the effects of these systems in healthcare [3]. Only four SAR systems (PARO [4], Aibo [5] NeCoRo [6] and Bandit[7] were reported so far in research on their care related effects. And even for these four systems, results are still limited, as no clinical trials (RCT) are reported. Also no interventions were reported involving any of the four systems.

This paper reports a study aimed at developing interventions for the PARO seal robot (e.g.[4]), as preparation for an RCT to be executed in Dutch intramural care facilities with elderly dementia patients. PARO was selected for this purpose because, of the four systems mentioned, it is the only system with the European CE mark, guaranteeing basic technical robustness, reliability and intrinsic safety. Moreover, the large number of publications from the PARO developing team on application and effect support the potential of PARO (Figure 1).

The interventions proposed in this paper have been developed in collaboration with three Dutch institutions providing dementia care: Dignis, Sevagram and Proteion. These organizations are also involved in the RCT under development.



Fig. 1. Paro Robotic Baby Seal

2 Method

The application of Paro cannot be a goal in itself. The development of interventions involving Paro must be based on the potential of Paro to add value to existing care

provision. For this reason the development was based on the expertise of three care-providing organizations. Sevagram, located in Heerlen has in total 2500 employees, Proteon-thuis employs 1400 care professionals, and Dignis (part of the Lentis group) employs 4500 care professionals. All three offer both intramural and extramural elderly care spread over psycho-geriatric care and somatic care.

In collaboration with the three organizations 9 meetings were organized, three with each organization. Initially two meetings were arranged with each organization for the purpose of specifying goals, target groups and environments for the application of Paro in intramural psycho-geriatric care.

In one meeting, daily care providing personnel was involved, including nurses, diversional therapists and team managers. In the other meeting therapists and doctors were involved, including psychologists, physical therapists, occupational therapists and medical doctors. In total 30 staff members were involved in those meetings. The two groups met separately to offer opportunity for all staff to express their opinions without hierarchical confounding.

During both meetings at each site an identical procedure was applied. First an interaction was arranged between a resident patient and Paro, witnessed by participating group of staff. For the involvement of each patient, written informed consent was obtained from their legal guardian. Paro was introduced by one of the staff members and spontaneous interaction was observed and recorded on video. This unstructured interaction was meant to introduce Paro functionality to the attending staff members. Following this, a Metaplan [8] session was held; participants were invited to record their individual views on 1) potential goals, 2) target populations and 3) environments for Paro application. These views were subsequently shared within the group and followed by a group discussion to clarify the collected material. Results of all discussion meetings were gathered and analyzed in combination.

After the results of the first meetings were reported back to the participants, a third meeting was held at each organization for which the therapists and medical doctors were invited. The aim of this meeting was to prioritize the purposes of Paro interventions and determine the type of outcomes that could assess the added value of each of the Paro interventions.

The data from all the meetings were brought together as a basis for the formulation of intervention(s) by the research team. Concept interventions were then sent to the participants of the meetings and their feedback was used to formulate the final interventions.

3 Results

On the basis of the meetings at the three care organizations a collection of goals for applying PARO in intramural dementia care was brought together. These goals concerned both preventive and therapeutic applications. The target patients for which application would be suitable could not be specified in general terms. The participants agreed this to be highly individual and difficult to outline relevant patient characteristics without further experience with the application of PARO in practice.

The collected goals were categorized into three main groups.

- Application of PARO for therapeutic purposes. Depending on individual needs PARO can stimulate perception, psychological functioning, psychosocial well being and social behavior. For patients at risk availability of PARO can re-activate the person at individual level.
- Application of PARO to facilitate daily care activities, making use of the attention focused on PARO or its comforting ability when made available. For care providers the presence of PARO during daily care activities could enhance patients well being and thus facilitate the required care activities. Normally, for some patients these daily activities cause anxiety or stress making the task of the care giver more difficult.
- Application of PARO in support of social visits. For family members it was reported that due to the progressing dementia attractiveness of family visits to dementia patients is difficult to maintain. The activating qualities of PARO on the patient could be used to provide a shared focus point for both the patient and the family member(s) and stimulate the attractiveness of visits.

Within each of these three categories a PARO intervention was specified. The first intervention aims at providing comfort to individual distressed dementia patients in critical timeslots during the daily routine. Distress is a common symptom of dementia and may result in distorted day-night activation patterns. PARO is to be used to stimulate perception and activate attention, leading to a sense of purpose in activities. The purpose of this PARO intervention is highly individual and in general of therapeutic nature.

The second PARO intervention aims at facilitating the provision of care by professionals. PARO could bring about a desired mindset of the patient, lowering common resistance to ADL care tasks executed by the staff. It might function as a diversion or as a means to bring about a more cooperative mood.

The third PARO intervention aims at supporting social contact between a dementia patient and visiting family members or acquaintances. PARO is then used as an intermediary, facilitating shared attention and conversation.

In each of the interventions the application of PARO and supporting activities are described at very practical level. The descriptions clarify the intention and actions to the professional. In addition, information is provided for involved care professionals and family members to prevent common prejudice and resistance to the application of a robotic ‘toy’ for their relative. The descriptions offers easy accessible information on the robot PARO, its purpose and ‘how to’ in psycho-geriatric care provision.

The formulation of the three PARO interventions not only were intended to structure the application of PARO in daily care provision. In the context of the ongoing study into the effectiveness of Social Assistive Robots the interventions are intended to define the way PARO will be evaluated in Dutch care provision during an RCT. The evaluation criteria to be connected to these interventions were the topic of the third meetings. Participating care professionals reflected on the evaluation criteria as used within care practice and their suitability for evaluating the PARO interventions.

Primary outcome for the first interventions was behavioral change. As assessment tools the Dutch GIP scale was suggested (Behavior Observations scale for Intramural Psycho-geriatric (only in Dutch) [9]. Because of the highly individual nature of

problematic behavior in psycho-geriatric it was recommended to consider tailored versions of observations assessing relevant behavioral change in sufficient detail. As secondary measures mentioned were Depression, with the Cornell Scale for Depression in Dementia (CSDD) as assessment tool [10] and Medication use, to be reported by the responsible physician.

For the second and third intervention the preferred primary outcome was again patient behavior and its impact on either care provision or family visits. It was stressed that suitable assessment criterion needed to be very easy to administer as it would need to be part of the daily care routine. As a solution a tailor made behavior checklist for each patient was suggested, possibly in combination with the Goal Attainment Scale (GAS) method (as originally proposed by Kiresuk & Sherman [11]). Selection or development of the assessment tools will require addition research as part of the RCT development.

4 Conclusion

This study aimed at the development of interventions involving the robot baby seal Paro. Inspired by the intuitive appeal of PARO, three care institutions combined resources and requested a structured development of PARO interventions to ensure effective future application of the robot. The resulting interventions provide not only hands-on instructions for implementing the robot in the provision of daily care, but also a description and definition of the expected effects from PARO and the method to assess these effects. Additional to these descriptions, information for both professional care and informal caregivers is provided to support the effective uptake of the PARO interventions. The set of interventions also define the application of PARO as will be studied in the subsequent RCT.

The three developed interventions differ in their impact on the provision of care and therefore in the added value they may have. The first intervention aims for a therapeutic effect, the other two interventions emphasize practical benefits. In the application of PARO this provides the opportunity for care organizations to make an informed decision on why and how to introduce PARO as an intervention. For care financers it provides the opportunity to assess the basis for reimbursement of PARO involved interventions. Application of care robots in general can benefit from the definition of interventions embedding robots. An essential step in this process is sound assessment outcomes of care robotics in daily care provision. Without such assessment reimbursement will continue to be a problem, undermining the application and further development of socially assistive robotics. The results of this study provide the basis for the methodology of the RCT to be executed.

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Short Term Effect Evaluation of IROMEC Involved Therapy for Children with Intellectual Disabilities

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Abstract. Research tends to show a reduced playfulness in children with intellectual disabilities. This hampers engagement in play which in turn is a threat to participation in children's most important occupation, potentially inhibiting health and well-being. The reported study evaluates short-term effects of the IROMEC robot toy supporting play in an occupational therapy intervention for children with intellectual disabilities. Three young children took part in this single-subject design study in which the robot intervention alternated with traditional toys guided by the responsible occupational therapists. Evaluation was performed through Test of Playfulness (ToP), the IROMEC evaluation questionnaire and qualitative evaluation by the therapists. Results indicated large differences within subject in ToP, gradually increasing IROMEC questionnaire scores, qualitative results indicated appreciation of the robot potential for therapists and children. Long term effect evaluation should verify these positive indications resulting from use of this innovative social robot for children with intellectual disabilities.

Keywords: IROMEC, effects, play robot, therapy, intellectual disabilities.

1 Introduction

Play is an essential activity in the development of any child [1,2]. Children with disabilities are often hampered in their play because of the functional limitations brought about by the disability and, as a result, will suffer developmental delay. This is the case for children with physical, sensory and/or intellectual disability.

Specifically in children with intellectual disabilities research tends to show a reduced playfulness [3,4,5]. A low level of playfulness leads to lack of engagement in play [6]. This, in turn, is likely to inhibit participation in children's most important occupation, which play is. In the long run this threatens health and well-being [7,8].

Dutch occupational therapy for children aims to enhance quality of life through engaging in meaningful occupations and enhancing skills to stimulate the child's

development in general. Within occupational therapy, play is traditionally used ‘as a means’ to foster functional abilities and, more recently, ‘as an ends’ valuing the engagement in the occupation itself [8]. New interventions that can foster the level of playfulness for children with intellectual disabilities should be considered for application. In this context it is expected that the introduction of robot involved play in occupational therapy will have a positive influence on the level of play and playfulness for this target group. This claim however has not been experimentally confirmed satisfactory, as only very few systems have been evaluated for their effectiveness so far [9].

In the IROMECE project an innovative play robot was developed for this purpose. This robot was developed within the European project IROMECE, co-funded by the European Commission within the RTD activities of the Strategic Objectives SO 2.61 ‘Advanced Robotics’ of the 6th Framework Programme. It is a modular and configurable robotic platform that can be used in therapy and education [10]. It was developed specially for children with Autistic Spectrum Disorder, severe motor impaired children and children with intellectual disabilities. The appearance of the play robot is a mix of humanoid and vehicle like, depending on the horizontal or vertical position.

Effects of the IROMECE play robot have not been extensively studied within the IROMECE project, but technical robustness and safety, as well as usability for the intended users of the system have been established [11]. Besides methodology to conduct therapy sessions with IROMECE [9, 11] structured by (ICF based) therapeutic aims [12], a related assessment tool the IROMECE questionnaire was developed [13].

The study reported in this paper aims to examine the short-term effect of a robot involved play intervention within occupational therapy on the level of playfulness of children with intellectual disabilities aged 3-5 years in comparison with traditional toys based therapy.



Fig. 1. IROMECE robot in horizontal position

2 Methods

The short term effect evaluation was executed as a quasi experimental single-subject time series design. Three children ranging in ages from 3 to 5 years with intellectual disabilities were included in the study. The participants were recruited through purposive sampling at the Adelante children rehabilitation centre in Valkenburg, the Netherlands. This is a rehabilitation centre with an integrated school for special education for motor impaired children and or intellectual disabilities. The children were included after written informed consent of their parents, in accordance with the Dutch legislation, after ethical approval of the responsible ethical committee at Atrium hospital Heerlen.

The IROMECE robot was embedded in a therapy session, in contrast to “therapy as usual”. Both types of therapy were provided by the child’s own occupational therapists, who were all trained in the use of the IROMECE play robot for the purpose of the

study. The three children, two girls and one boy, showed intellectual disabilities due to cerebral palsy with hemiplegia, spastic diparesis, and general developmental delay. Intellectual abilities were in all three cases limited, resulting in an intelligence quotient between 50 – 69 (SON-R) [14]. They have several kinds of therapeutic services provided from Adelante, occupational therapy was provided 2 times a week in single sessions lasting 30 min.

Therapy as usual (A) was limited to play with predefined toys depending on the therapeutic objectives defined by each occupational therapist, individualized for the particular child. The robot involved play intervention (B) comprised playing predefined play scenarios with the IROMEC play robot, again selected on the basis of the therapy aims for the individual child. The testing period comprised in total 12-14 therapy sessions with each child over 6-7 weeks. In blocks of three sessions therapy versions A and B were used alternating (A-B-A-B). For each child, prior to the therapy session, objectives for the therapy were set, on the basis of which the traditional toy was selected (condition A), the IROMEC scenario was selected (condition B) and finally also the sub-set of questions of the IROMEC questionnaire was established. Although the therapy objectives were kept identical for each of the children during the whole period, some variation in therapy objectives related to specific focuses in single sessions appeared.

Data gathering involved firstly (a) scoring of each child on the Test of Playfulness (ToP 4.0) [5], based on video-registration of the therapy sessions. The observation of playfulness can be guided according to the different elements of playfulness as follows: intrinsic motivation; freedom to suspend reality; internal control; and framing. Playfulness was assessed after each therapy session by the experimenter. Secondly (b) scoring on the IROMEC evaluation questionnaire [12,13] was administered by the occupational therapists after each phase (A-B-A-B). This questionnaire assesses the child's functioning on a wide range of functional areas following the ICF-CY [15]. On the basis of the wide range of human functioning this resulted in an extensive tool that benefits from narrowing down for specific purposes. The tool features a modular design that allows selection of a subset of items on the basis of the aims set out for the individual child's therapy. These aims are to be defined by the (occupational) therapist. Through this procedure the resulting tailored questionnaire is significantly reduced in size and contains only relevant items on the child's functioning with respect to the play therapy. In addition to the Test of Playfulness and the IROMEC tool, (c) the opinions of the involved occupational therapists were assessed regarding their perceptions on goal achievement after each therapy session using a visual analogue scale, and they gave (d) general feedback on appearance of the robot, usability and added value towards therapy.

3 Results

The study aimed to seek a difference in the level of playfulness assessed through the ToP and the effect of therapy assessed through the score on the IROMEC tool. In addition the validation of the therapists was assessed.

The results of the playfulness were gathered on the basis of observation of an occupational therapist, after satisfactory calibration of her ToP assessment characteristic.

The scores obtained for the participants varied over the sessions and the relations between the scores and type of intervention (A versus B) could not shown to be significant on the basis of initial analysis. This differed from what was expected at the outset of the study.

The scores on the IROMEC questionnaire were based on the subset of questions that are connected to the objectives the therapists set out to cover in each session. Over sessions and over the condition (A and B) the objectives for each child were in part identical. Additional objectives were pursued in single session related to the type of game or the toys included in the session. (e.g. for participant "Antje" *perception* was a continuous objective while *fine motor control in hand function* was a recurring additional objective). Scores on the IROMEC questionnaire can be compared within subjects, regardless of the objectives underlying the question subset used. The scores gathered with the IROMEC questionnaire were expected to rise over the total duration of the study. This was found for two (Ellen and Pieter) of the three children, for the third participant (Antje) the IROMEC score gradually decreased over the sessions.

The qualitative evaluation of the IROMEC robot was based on a number of topics to be validated through a 10-point VAS scale. Most positive rewarded were the *appreciation by therapist* (avg 7.0), *appreciation by child* (avg 7.0), most negative rewarded was the *added value to therapy* (avg 5.0). Contrasting the rather low appreciation of the added value for the participating children the therapists added that in general they did saw added value, but better matching between a child's need and the robot capability was required.

4 Conclusions

Playfulness is an important prerequisite for play activity. The assessment of the playfulness of the IROMEC play robot therefore is an important step in determining the added value of the robot supporting the development of play of children with disabilities. Establishment of long term effect of the IROMEC play robot cannot be expected from this study and will require additional research. The development process of children is a day-to-day process and proof of structural improvement can only be expected on the basis of long term involvement in IROMEC robot involved play therapy. Moreover, the development of children in the target group is of course dependent on many more factors then therapy sessions only. In this context the current study should be seen as one step in a series of evaluations to determine the added value of the IROMEC robot.

This study did not show clear positive effects of the robot involved intervention in terms of playfulness nor in the scores on the IROMEC questionnaire. The playfulness scores increased not significantly while introducing the experimental conditions and showed large variance within the subjects. Other variables such as mind-set of the child were mentioned as explanation for this. The IROMEC questionnaire scores indicated improvement for two of the three participants although this could not be specifically related to the robot intervention. The qualitative evaluations of the robot intervention were positive about the robot and its appreciation for both child and therapist, but less positive about the therapeutic added value for the involved children.

This was attributed by the therapists to the limited match between the participating children's needs and the characteristics of the robot as a toy. This was in particular true for one of the participants. For her playing with the robot proved to be a too big challenge. The children were selected for participation based on the formal inclusion criteria and the therapists judgement. It can be concluded that the inclusion criteria should be formulated in more detail and the therapists knowledge on the characteristics of IROMEC involved therapy increased prior to their selection of participants.

Another important issue is that the expectations on what to expect of the robot was, prior to the study, partly incorrect due to their limited experience with the robot. This may well lead to incomparability between the type of game brought about by the familiar toys compared the type of game resulting from the robot as toy. For example, as children were positioned behind a table for traditional therapy, in the IROMEC sessions the children moved throughout a room, stimulated by the movement of the robot. In the perspective of the therapists the latter condition induced other behaviour than intended in the session. An obvious positive effect of the study was the acceptance of the robot by the children and the therapists and the joy it brought to the children, as reported by the therapists.

This study did demonstrate the feasibility of assessing the effects of the robot therapy through the instruments used. Although elaborate, the ToP did function for controlled play, although developed for playfulness in free play. The IROMEC questionnaire proved effective in its modular, objective based, design.

The occupational therapists work with the children using the play robot clarified the actual potential of the robot in much more detail than could be expected through the introductory training alone. Through the involvement of the occupational therapists the study contributes to building acceptance of the application of a social robot in existing rehabilitation care provision. Moreover, the resulting experience with evaluating the IROMEC robot will support the further evaluation of the robot.

The results of the study add to the collection of evidence of the potential of social robots in occupational therapy because it details the nature of the required match between child and robot involved therapy. More elaborate and extensive data collection is obviously required to reach the position in which care financiers can be convinced to accept the costs of robot involved therapy. Such acceptance would open the way to have many more children benefit from the robot and also to further improvement and development of therapy involving social robots.

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Adaptive Robot Design with Hand and Face Tracking for Use in Autism Therapy

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Abstract. This research explores interactive games using hand and face tracking with a robot as a tool for autism therapy. The robot is equipped with a head and two arms, each with two degrees of freedom, and a camera. We trained a classifier to detect human hands and subsequently, used this classifier along with a standard face tracker to create two interactive games. In the first game the robot waits for the child to initiate an interaction by raising one or both hands. In the second game, the robot initiates interactions. These games are designed to increase attention, promote turn-taking skills and encourage child-led verbal and non-verbal communication through simple imitative play. This research makes two specific contributions: (1) We present a low-cost robot design which measures and adapts to a child’s actions during interactive games and, (2) we train and test a hand detector, based on Haar-like features, which is usable in various kinds of human-robot interactions.

Keywords: Human-robot interaction, hand detection, hand tracking, adaptive robotics.

1 Introduction

Robot-assisted autism therapy employs robots as social mediators for promoting and teaching communication skills in autistic children. Robots have been used effectively to engage autistic children in interactive game playing and research has demonstrated that robot-assisted autism therapy promotes increased speech and increased child-initiated interactions in children with Autism Spectrum Disorder (ASD) [4]. The goal of our research is to provide parents and therapists with an effective, widely usable, interactive robot that will broaden the impact of traditional therapies. Research in robot-assisted autism therapy typically emphasizes specific objectives for ideal human-robot interaction including an increased attention span, eye contact, proactive interaction with the robot initiated by the child, verbal and non-verbal cues, turn-taking, imitative game playing and overall use of language.

In this paper, we describe a simple interactive robot, named CHARLIE (CHild-centered Adaptive Robot for Learning in an Interactive Environment), which uses a turn-taking game for the purpose of engaging autistic children during therapy. See Figure 1. The robot is designed with a head and two arms, each

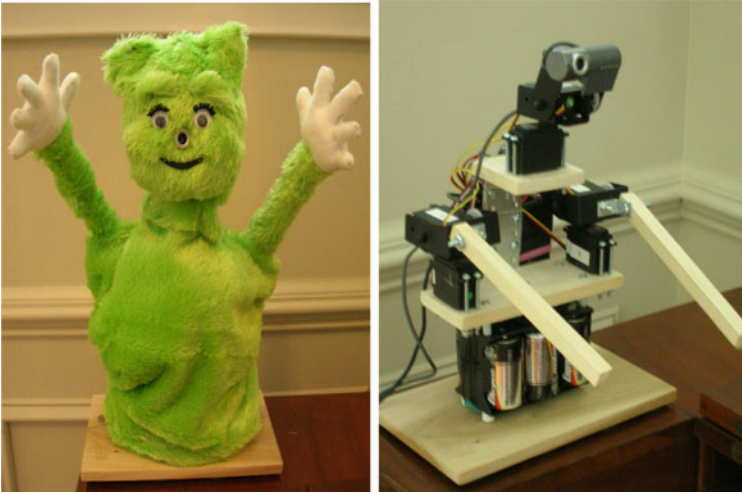


Fig. 1. CHARLIE. [left] Completed robot. [right] Internal structure.

with two degrees of freedom, and a camera for face and hand detection. The camera is mounted inside the robot head which moves, as needed, to maintain visibility of the face whenever possible. We show that basic commodity hardware is sufficient to implement face and hand tracking for interactive games designed for use in autism therapy. Ongoing research focuses on designing and conducting clinical studies with autistic children in order to test and measure the effectiveness of using CHARLIE for promoting turn-taking and basic communication skills. Due to its relatively low cost and inelaborate hardware, CHARLIE is intended to be accessible to a larger population of children than many of the robots currently used for autism therapy. Because of its hand tracking capability, CHARLIE can autonomously participate in a wider range of user-driven, interactive games where robot actions are determined by the actions of the child. Furthermore, the robot can automatically collect information about the child’s interactions and provide a summary report for evaluation at a later time.

In general, the implementation of a robust hand tracking system can greatly improve the quality of human-robot interaction, especially when the robot is intended for rehabilitative or therapeutic purposes. First, the progress and preferences of a user can be measured objectively by monitoring response times, length of engagement and number of user-led responses. This information, combined with the amount of verbal and non-verbal communication during a session, can provide valuable information pertaining to a user’s progress. In the longer term, we expect the insight gained from this research to generate deeper understanding of the unique nature of robot interactions with the developmentally disabled, leading to broader innovations in robot software for therapy and assistance to this population.

The remainder of this paper is structured as follows. Section 2 is a review of related work. Then, we detail the fundamental methodology and approach underlying the robot and game design in Section 3. In Section 4, we present a description of the preliminary test design and results. We conclude the paper with a summary of our research and a brief discussion about future work in Section 5.

2 Background

Autism therapy ultimately seeks to promote human-to-human interaction. Over the past decade, the use of robots as social mediators has been explored as a tool for supplementing traditional autism therapies in order to teach and improve social skills. Robots are well-suited for interactive games with autistic children since they tend to be perceived as predictable, non-threatening, and are able to perform repetitive tasks consistently and reliably [10,13]. Most importantly, an increase in basic social and interaction skills has been observed when using robots for turn-taking and imitation games [6].

Some of the most promising results from robot-assisted autism therapy include an increased attention span, eye contact, child-led speech, improved turn-taking and imitative game playing skills and overall use of language [5]. Minimally expressive robots such as KASPAR [15] have been used to explore the efficacy of robot-mediated therapy for autistic children. That research revealed that relatively low functioning autistic children, who would not normally seek physical or eye contact, directly engaged with the robot and, in some cases, proactively touched and gazed at co-present others during sessions with KASPAR.

Other research used for assisting autistic children has resulted in the design and development of various robotic systems. With Keepon [8], it was observed that a very simple robot interface could be used to engage the attention of autistic children and facilitate social interaction. Results obtained from the Bubblebot research [17] showed that human-robot and human-human interaction is increased with a responsive robot whose actions are contingent on user commands. The IROMEC project [12] identified three play scenarios and five distinct developmental areas most beneficial for collaborative, interactive play with autistic children [7].

The robot described herein incorporates key characteristics from each of the above studies. The toylike, non-humanoid appearance of the Keepon and the user-directed modality of the Bubblebot were used as the basis for the development of the robot architecture and the three types of play scenarios identified in the IROMEC study, (1) turn-taking, (2) sensory reward and (3) imitation were used to design the games detailed in this paper. The unique contribution made by this research is the low-cost design and additional functionality provided with the face and hand tracking system. With face and hand tracking, the robot will not only be able to participate in qualitatively different interactive games but it will also allow the robot to collect pertinent information regarding a child's specific progress that may be difficult or impossible to obtain otherwise.

3 Methodology and Approach

The approach taken for this research is based on the integration of robot and game designs that are known to be effective with autistic children. The five specific design components considered in this paper include robot hardware and design (Section 3.1), face and hand detection (3.2), face and hand tracking (3.3), interactive game design (3.4) and data collection (3.5) .

3.1 Robot Hardware and Design

Recent research has shown that robots with a simple interface are generally better received initially by children with autism, than robots with a more realistic, human-like appearance [14]. The implication is that low-tech robots, when designed appropriately for the particular needs of the autistic child(ren) they will serve and the context in which they will be used, can be used effectively to teach and promote social skills. In addition to the low cost mentioned above, CHARLIE’S physical design is intended to be toy like to create a friendly and approachable outward appearance and to more easily attract the attention of a child.

CHARLIE’s hardware includes 6 servos, 3 pan-tilt platforms, an 8 channel servo controller, a consumer-grade web cam, and 2 D-cell battery packs. The robot’s body is padded for safety, and its outer surfaces are covered with a bright green, fur-like material to achieve a non-threatening appearance. During active game play the child’s attention is typically focused near CHARLIE’s hands, so one LED is embedded in each of the hands to provide positive feedback during interactive games. Exclusive of the computing hardware, the retail cost of the robot’s components is approximately 200 USD. In a production version of this robot, a computer could be integrated into the robot’s body, or users could connect via USB to a standard laptop or desktop PC.

3.2 Face and Hand Detection

The Open Source Computer Vision Library (OpenCV) [2], a cross-platform library for real-time computer vision applications, was used for training the hand classifier and for the implementation of hand and face detection. OpenCV provides a facility for object detection based on an extended set of Haar-like features [9]. Informally, this method works by screening small portions of an image for visual characteristics of the target object. To train a classifier to identify a specific class of objects, OpenCV uses Adaptive Boosting (AdaBoost) [16] to create a cascade of boosted classifiers defined over these features.

Face detection is a well-studied problem [18,19], and effective face classifiers are freely available through OpenCV. Conversely, robust and real-time hand detection in diverse environments, is a topic of continuing research. Numerous approaches for developing robust hand detectors have been explored [11,1], but



Fig. 2. Images used to train the hand detector. [top] Positive examples. [bottom] Negative examples.

the resulting classifiers have not been made available to the research community. Further, hand classifiers that are freely available are not accurate or efficient enough for our application. In order to implement a hand detector suitable for our purposes, we trained a new hand classifier to detect hands in various lighting conditions, rotations, scales and finger positions. Approximately 750 positive hand images of various size, color and position and approximately 3300 negative images were collected and cropped to a uniform pixel size of 40x40. Representative examples are shown in Figure 2. To create additional positive training samples representing variations in lighting, rotation and scale, ten distortions were applied to 100 of those samples, yielding a total of approximately 1750 positive hand samples.

We trained a twenty-stage cascade on these samples, yielding an error rate on the training set approaching zero. Section 4 presents a quantitative evaluation of the classifier performance.

3.3 Face and Hand Tracking

Face and hand tracking were implemented using the Continuously Adaptive Mean Shift (CAMSHIFT) algorithm [3]. CAMSHIFT incorporates the MEANSHIFT algorithm which is based on a nonparametric technique for climbing density gradients to find the peak of the probability distribution of the position of a given target object. For face and hand tracking, this translates to identifying the center of the target color distribution in a given video frame. The CAMSHIFT technique was implemented for this research because it is fast (making it ideal for use in real-time tracking applications), with relatively robust accuracy. This tracking method improves performance by eliminating the need to repeat the face and hand detection for each frame of the video. To overcome errors resulting from drift in the CAMSHIFT algorithm, the robot periodically repeats the full face detection process. In the event that the robot cannot detect the face, the robot head is reset to a neutral position and searches outward in an increasingly larger area.

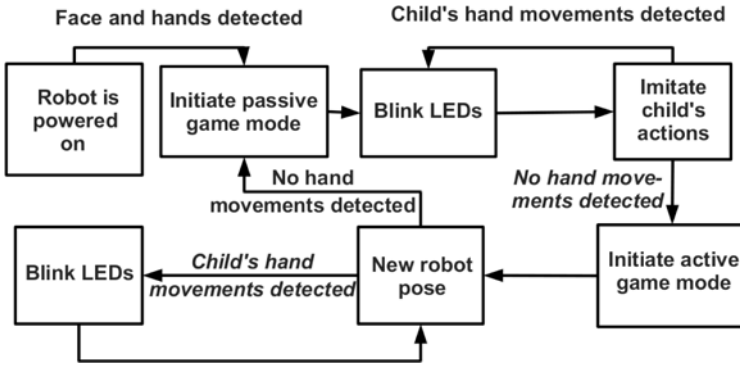


Fig. 3. State diagram for CHARLIE’s interactive games

3.4 Interactive Game Design

As detailed in Figure 3, the robot has two states: passive and active game modes. Within each of the two game modes, there are five poses: neutral (both hands down), left hand raised, right hand raised, both hands raised and peek-a-boo, as shown in Figure 4. In order to give the child initial control over the robot’s actions, the default robot state is the passive game mode. Once the robot detects and begins tracking the child’s face and hands, the robot indicates that it is ready to interact by moving to the neutral pose and blinking the LEDs in its hands three times. The robot then immediately enters the passive game mode and waits for the child to initiate a game by raising one or both hands. As the child’s hand movements are detected, the robot responds by imitating the child’s hand positions and lighting the LED in the corresponding hand while simultaneously detecting any additional hand movements. If ten seconds elapse without any detected hand movement, the robot will transition to the active game mode.

During the active game mode, the robot initiates a new game and attempts to engage the child by raising or lowering one or both arms, or beginning a game of peek-a-boo. Each pose assumed by the robot in the active game state is selected randomly in order to avoid repetitive patterns of poses. When a positive outcome is detected (the child successfully imitates the robot’s pose), positive sensory feedback is generated by the robot. A positive sensory response entails the robot lighting a small LED in the hand corresponding to the raised hand or hands of the imitated pose. As with the passive game mode, the robot will wait ten seconds for the child’s response. If ten seconds elapses and a positive response has not been detected, the robot will transition back to the passive game mode, waiting again for the child to initiate a new game.

3.5 Data Collection

There are two distinct kinds of user interaction information collected by the robot. Information pertaining to the user’s overall progress such as (1) the total



Fig. 4. CHARLIE poses. [top left] Left hand high. [top center] Right hand high. [top right] Both hands high. [bottom left] Neutral. [bottom right] Peek-a-boo.

length of active engagement (time spent actively engaging in either passive or active mode), (2) number of child-led actions and (3) the number of successful interactions is continuously captured during each session. At the end of the session, this information is used to create a user progress report for analysis and for future sessions with the same child. The second type of user information, such as the length of the intervals between interactions, is used for controlling the robot state.

4 Preliminary Tests

As a proof of concept for CHARLIE's effectiveness, preliminary tests were conducted with a small group of typically developing children. See Figure 5. A relatively large age range (4-11 years) was selected primarily to test the reaction times of the robot when used with children of varying levels of ability. Each child participated in an 8-10 minute session, in which both game modes were tested and the accuracy of the hand and face detectors was measured. The duration of each game mode was recorded to ensure that adequate time is given for the child to respond before a transition is made to the alternate game mode and the effectiveness of the positive sensory feedback (LEDs in hands indicating successful detection) was assessed.



Fig. 5. Children Interacting with CHARLIE

It is important to note that preliminary tests were conducted strictly to test the speed and accuracy of the face and hand detector and to assess the appropriateness of CHARLIE’s timed responses during game play. Future studies with autistic children will be designed to test and measure each child’s progress in terms of specific turn-taking through imitation objectives including length of engagement, number of child-led actions and verbal or nonverbal communication.

The accuracy of the face detector and tracker was determined by calculating the ratio of successful face detection time to the total session time. The face detector averaged an accuracy of 86% across all sessions and users. This accuracy rate is artificially low because it includes as misses the aggregate time when participants moved outside of the video frame. The accuracy of the hand detector and tracker was calculated similarly. In a typical session, users averaged 33 child-initiated hand movements and imitated 16 robot movements per minute. The hand detector accurately detected the child’s hands an average of 92% of the total session time, with 244 hits out of 265 total hand events.

Nearly all of the children expressed a preference for the passive game mode, where the robot imitates the child’s hand actions, and their comments were supported by the significantly greater amount of time each of those children spent in the passive mode compared to the active mode during their respective sessions. Our hypothesis is that autistic children interacting with CHARLIE may also prefer the passive game mode, since this affords the child the greatest amount of control over the robot. We consider these preliminary results as an important proof-of-concept in preparation for controlled tests with autistic children.

5 Future Work and Conclusions

This research resulted in the design and development of a low-cost, adaptive robot and a dual-mode interactive game for use in robot-assisted autism therapy. One of the aims of this research was to create a robot that is financially accessible to a greater population of therapists and families with autistic children in order to broaden the impact of traditional therapies. The second objective was to

develop a hand detector enabling a larger scope of interactive games in which the robot can engage autonomously. Achieving this second objective also allows for real-time collection of important user interaction information specific to the preference and progress of each child undergoing autism therapy. Collectively, these contributions produce a new robot which is designed to be child-centered, adaptive to user preference, and to fulfill a key supportive role for therapists by automatically generating user progress reports.

Work on the hand classifier is ongoing in order to produce a more robust hand detector with improved accuracy. To further improve the accuracy of hand and face detection and to explore the remote detection of user stress levels, we are researching the use of infrared sensing to collect physiological information using a prototype similar to the one used for this research. Continuing work is also being conducted to identify and develop measures of success so that user information collected during an interactive game can be used to assess the child's readiness for more advanced, child-initiated games such as collaborative group play and story-telling.

Field tests with a population of autistic children are being designed and planned for Fall 2010. Discussions with clinicians currently working with autistic children from the South Carolina Department of Disabilities and Special Needs and the South Carolina Autism Treatment Network most recently resulted in the recommendation that young autistic children undergoing early intervention, Applied Behavioral Analysis (ABA) would be good candidates for interacting with CHARLIE. A cornerstone of ABA relies on the assessment and documentation of interventions to ensure their efficacy and to promote progress from one session and from one therapist to the next. In addition, it was recommended that two physically distinct robot prototypes be tested. To complement the "soft and fuzzy" appearance of CHARLIE, a robot with a more mechanical, robotic outward appearance will be constructed in order to appeal to a broader scope of children. Ultimately, three general elements will be considered for evaluating CHARLIE's design: (1) children's response to CHARLIE's physical appearance, (2) overall engagement of the child undergoing therapy with CHARLIE and, (3) effect on turn-taking and communication skills. Specific measures of success are currently being developed.

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Selecting When Acting: How Human Perception Is Tuned to Action Goals and How Robotics Can Benefit from That

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Abstract. This paper reviews theoretical perspectives and empirical evidence speaking in favor of a close link between action control and perceptual selection in humans. Results from behavioural studies, neuro-imaging, human electrophysiology as well as single-cell studies in monkeys are described. These data as well as theories are brought forward to argue that close connection between action and perception should be considered in designs of artificial systems. Examples of such systems are described and the application of those approaches to robotics is stressed.

Keywords: Human action planning, perceptual selection, social robotics.

1 Introduction

The world provides our senses with an abundance of input. It would be rather detrimental to process all the information – how could we then act efficiently? Imagine a person playing baseball who is just about to hit the ball. If the brain processed all information without any prioritization, the person would be severely distracted by the falling leaves, sound of the nearby waterfall, and other stimuli reaching the sensory apparatus. Yet, we all know it is not the case – healthy brains are able to efficiently filter out irrelevant information and focus on what is relevant for the current task. Researchers have been addressing this ability of the human processing system and termed it selection (or attention) mechanism. Despite a lot of progress in the attention area, many questions still remain to be answered. Among many others, a still open question is: how does the brain decide on what is relevant? One way of selecting what is relevant can be related to given actions an agent is intending to perform. Again, in the baseball example, depending on whether one is to hit the ball or catch it, different aspects of the ball will be prioritized. In catching the ball, grip aperture is important, and hence, size and shape of the ball needs to be processed with priority. In case of hitting the ball, its location is the most important feature. In neither of the cases is the colour of the ball relevant. A mechanism that allows selecting relevant features for particular action types and thus, enables efficient action planning we will term “action-related selection”.

In the following, we will review selected theories and empirical evidence stressing the connection between action and perception domains. We will argue that when considering mechanisms of selection, one cannot focus on the perceptual processes in isolation without taking into account the impact action planning has thereupon. We believe this is of high importance for designing artificial systems, especially systems that are to interact with humans in an efficient manner.

The views presented in this paper might be an example of a framework that belongs to the embodied cognition approach in the cognitive sciences (for a review see [1]). In contrast to traditional accounts in cognitive sciences, embodied cognition views the cognitive capabilities of humans not in isolation from action, environment, and the body, but rather as embedded in the interaction between the three. This might imply that human's inner representations do not consist in abstract symbols and operations thereupon, but rather on simulated actions and interactions with the environment. A prototypical example of such an embodied representational architecture is the work of Lynn Andrea Stein [2] implemented in a robotic system of Toto and MetaToto – designed by Maja Mataric [3]. Those systems, equipped with sensors to detect walls, corridors and obstacles, develop inner representations of the environment that are “action-related”. That is, instead coding landmarks in an abstract way, these systems code them in terms of the robots' movement and perceptual input. Such “embodied” approach might prove an extremely efficient way of designing artificial systems, given that growing evidence speaks in favour of a close coupling between perception, action and environment in humans.

2 Ideomotor Theories on Action Planning

As highlighted in the baseball example, humans are not passive observers of the surrounding world. Humans act and interact with their environment – and in order to efficiently do so, humans must have developed means to optimize action planning. According to ideomotor perspectives, e.g., [4], [5], [6], human action planning is based on representations of desired action goals. These, in turn, consist in anticipated sensory consequences of the intended actions. How are such representations possible? Greenwald [4] as well as Hommel et al. [5] suggest that this is possible thanks to life-long experience with various actions having not only proximal effects (re-afferent consequences of particular movements) but also distal effects, i.e., sensory consequences of changes in the surrounding that are related to the performed action (e.g., if one strikes a ball with a baseball bat, one will see the ball moving and also hear a sound of the ball hitting the bat). For example, Harless [7] postulated that acquiring voluntary action control mechanisms takes place in two stages. In the first stage, actions are carried out randomly. The effects of those actions are perceived and memorized. Subsequently, in the second stage, as the links between given action types and their sensory consequences are already available, they can be used to intentionally plan actions to produce desired effects. Such a view on development of voluntary action control fits to everyday observations of how babies first randomly move and only subsequently learn to control their actions by anticipating sensory consequences thereof. When the links between actions and their perceptual consequences are acquired and action effects can be anticipated, the human brain is able to evaluate

veridically if the actual consequences of particular actions match the anticipated/desired ones (for a similar account, see forward models, e.g., [8]).

3 Common Coding Perspectives

If action planning happens through representation of anticipated sensory consequences of actions, there must be means for efficient “communication” between action and perception domains. The common coding perspectives, e.g., [5], [6] postulate that action and perception share a common representational code. That is, there is no need of “translation” between action and perception domains as both encode information in the same format. The format presumably consists in a distributed network of features [5] that are bound together across domains to form events. In particular, in the above baseball example, if hitting the ball with a bat is always associated with a given sound and a given movement of the ball, the action of striking the ball with the bat and the perception of sound and motion will probably tend to being bound together to one event.

Not only do action and perception codes share a common representational format but they also are functionally equivalent. This claim presupposes that perception is an active process: perceiving means active acquisition of information through selective mechanisms, eye-, head- and other body movements. On the other hand, action would not be successful or efficient without perceptual feedback. Therefore, action and perception serve the same purpose: efficient interaction with the environment. Importantly, however, the common coding theories refer to representations of actions in terms of their distal effects but not proximal sensory effects. That is, common codes between perception and action do not refer to such characteristics like neuronal pattern of muscular activity while performing a movement. This is a crucial claim as it would rather be implausible that neural activity related to a stimulation of retina by a given visual input is equivalent to muscular activity related to performing a grasping movement.

4 Evidence for Interaction between Action and Perception

Evidence for bindings between perceptual and action features comes from, e.g., studies reporting partial-repetition costs [9] or inverse-compatibility effects [10]. In another line of research, Craighero et al. [11] demonstrated that preparing for a movement (grasping, in the case of their studies) influenced visual detection dependent on whether the visually presented stimulus shared characteristics of the to-be grasped object or was incongruent with it. Neuroimaging techniques also provided evidence for an automatic activation of motor areas when a predictable sequence of stimuli implied certain actions related to those stimuli. For example, Schubotz & von Cramon [12] conducted an fMRI study in which participants were presented with sequences of stimuli: either visually presented disks of various sizes or sounds of various pitches. Participants’ task was to judge whether certain elements of the sequence matched the sequence “rule”: e.g., if the sequence consisted in increasing size, the final three elements were also increasing in size. The authors observed neural activity in premotor

areas of the brain that are usually involved in hand movements when sequences of visually presented disks of different size were observed. On the other hand, premotor areas involved in articulation were activated when judgments were concerned with auditory stimuli of different pitch. These results show that processing perceptual features automatically activates actions that might be related with those features, and therefore, speaks in favour of strong action-perception links. Moreover, these studies stressed the importance of human ability to anticipate certain steps in a predictable sequence which might be the base for action understanding, and therefore, might involve action-related areas of the brain.

All the above-described studies indicate that action and perception are strongly coupled and that such coupling presumably allows efficient action planning. That is, if efficient voluntary action plans consist in anticipation of perceptual action effects and if action planning is to be successful, then action and perception should have an efficient way of communicating. A common code is the most parsimonious solution to that problem.

5 Intentional Weighting: Action-Related Bias on Perception

If action and perception are tightly coupled, then selection mechanisms in perception should also be related to action planning. Therefore, similar selection mechanisms should operate on perception when a given aspect is task-relevant or action-relevant. This has been one of the main postulates of the selection-for-action view [13], the premotor theory of selection [14] or of authors arguing in favour of a close coupling between selection for perception and selection for action [15]. Authors supporting the idea of a common code, e.g., [5] have postulated the concept of “intentional weighting” that should operate on perceptual processing in a similar way as other types of weighting mechanisms, see e.g., [16], [17]. That is, neural activity related to given characteristics of the environment might be modulated by top-down control to fit a given task, e.g., [18], [19] or action [5]. Such biased processing has been observed in a laboratory setup. For example, Fagioli, Hommel & Schubotz [20] designed an experiment in which they observed that participants tuned their perception to a concurrently prepared action. In a similar line of reasoning, Wykowska, Schubö & Hommel [21] designed an experiment in which participants performed two tasks: a perceptual task that consisted in detecting a smaller circle (size target) or a lighter circle (luminance target) among many other circles presented on the computer screen (a typical visual search task). The responses in this task were to be made on a computer mouse with one key being related to the target present trials and another key being related to target absent trials. The second task: a grasping or pointing movement was performed on items of especially designed device. This task was executed with a different hand than the one used in the perceptual task. The experiment was designed to create two congruent perception-action pairs (size with grasping and luminance with pointing) - as it was assumed, in line with the ideomotor theories, that through lifelong experience with grasping, humans have learned size to be relevant for grasping whereas luminance (feature allowing fast localization) to be associated with pointing. Importantly, as described above, the two tasks of this paradigm were experimentally entirely unrelated – both motorically and perceptually. Thus, the results showing

congruency effects (better performance in search for size when grasping as compared to pointing and better performance in search for luminance when pointing as compared to grasping) indicate that the facilitation of certain feature detection occurs at the representational level in the brain that links action and perception codes – and it is not due to motor priming (different effectors) or perceptual priming (different objects in the visual search and in the motor task). These results speak in favour of a close coupling between perception and action and allow for a speculation that it is a similar mechanism biasing perception with relation to action planning as the mechanism postulated in other attention theories, e.g., [17].

6 Ecological Approach and the Concept of Affordances

The common coding perspectives share certain aspects of their account with the ecological approach of Gibson, e.g., [22]. The ecological approach also stresses the idea of active perception and is strongly related to the concept of affordances. Affordances are characteristics of the environment or specifications thereof in terms of possible interaction with it. For example, a cup would have a (learned) characteristic of “something to drink from”. A chair would have a characteristic of “sittability”. As such, affordances constitute close links between action and perception. In other words, perception of an object carries information not only about such characteristics like “whiteness” or “roundness” but also about “graspability”, and as such activates the action system automatically.

Evidence for such affordances-based link between perception with action has been described by Humphreys and Riddoch [23], Tucker and Ellis [24] and a growing body of evidence provided by neuroimaging studies. For example, Grèzes & Decety [25] in a study using PET methodology showed that brain areas related to motor representation were automatically activated when participants watched objects that have certain action affordances. Similar results have been obtained by Grafton et al. [26] who recorded neural activity in premotor cortex in the area related to hand/arm movements when participants only passively viewed tools of common use (such as scissors, hammer, etc). Also single-cell studies on monkeys reported that neurons in certain motor-related areas of the brain are selective for object affordances, e.g., [27]. Therefore, all these results speak in favour of the idea that learned associations between certain objects and actions they afford might result in an automatic activation of motor-related areas while such objects are perceived.

7 The Mirror Neuron System

The revolutionary discovery of mirror neurons, see, e.g., [28] shifted the way of thinking about perception and action planning into a direction pointing to a common neural mechanism for these two domains. Mirror neurons have traditionally been observed in motor areas of monkey brains. Those neurons are related to planning a particular action but they also get activated when an animal only observes others performing that action type. Interestingly, those neurons are active also when a meaning of an action can be inferred from sounds [29] or other hints [30]. Therefore, these results have been brought forward as argument in favour of the idea that the mirror

neuron system has a functional role of action understanding [31]. Subsequent to the discovery of the mirror neuron system in monkeys, a large body of evidence has been collected for the analogue of a mirror neuron system in humans. EEG studies have shown that a certain EEG frequency (the μ -rhythm) is related not only to active movements but also to action observation, e.g., [32]. Finally, many brain imaging studies (PET, fMRI) revealed activation of motor areas when participants observed actions performed by others, e.g., [33], see [31] for a review. Certain authors have postulated that the mirror neuron system is responsible not only for action understanding but also for imitative learning, e.g., [34] and maybe even a base for communication and language acquisition, e.g. [35]. Some authors challenge the view that the mirror neuron system is specialized in action understanding and/or action imitation stressing the point that those areas are also involved in predictions of subsequent steps of regular sequences of stimuli, e.g., [12]. As such, action understanding might only fall within the broad category of anticipatory processes involved in known or predictable sequences. In either case, the mirror neuron system is a prominent example of close action-perception links which only shows how much readiness for action is involved in perception of the external world and selection mechanisms.

8 Application for Social Robotics

All the above considerations, theories and empirical evidence have been brought forward to argue in favour of a close coupling between action and selection mechanisms in perception. This has been described in order to emphasize that design of artificial systems needs to take into account such neural architecture and functionality of the human brain. This is important for a few reasons: one is that it might be beneficial to draw from evolutionary solutions when designing robots. Current artificial robotic systems have limited computing power and therefore, it should definitely be advantageous to implement certain selection mechanisms especially in the case of fast real-time systems that produce very rich and fast data streams. When deciding what sort of selection mechanism should be implemented, “copying” from evolution seems to be the most efficient way to solve the problem. Such an approach to design of robots that are to assist humans in the kitchen has been described in [36]. Another important argument for designing artificial systems based on similar mechanisms as those that operate in the human brain is the need for behaviour similar to humans for the sake of safe and efficient human-robot interaction. If robots are to accompany humans, they should produce behaviour predictable for humans, and this might be possible only when similar computing architecture is employed. Moreover, also robots need to be equipped with systems that understand the meaning of human actions. Here, the evolutionary solution might prove particularly useful. This direction has been taken in the work of [37] in which the researchers designed a model of functioning of the mirror neuron system that has been implemented in a humanoid robot which acquired knowledge about objects in terms of their affordances, became capable of action recognition, and finally managed to mimic actions performed by a human on various objects. The influential work of Mataric and colleagues has followed similar direction. For example, in [38] Billard & Mataric reported results of a validation study of their

biologically-inspired connectionist model that imitated human arm movements. The model consisted of a hierarchy of neural networks that represented the functionality of brain areas involved in motor control. For example, the “lowest level” network represented the functionality of spinal cord, another one represented cerebellum, two networks simulated the role M1 and PM cortices, and finally, there was a network that represented visual perception at the level of temporal cortex. Most importantly, the network representing the workings of the PM cortex translated and linked visual representations of observed actions to motor representations. More specifically, nodes of PM transferred the activity of the nodes in the “visual” network into activity of M1 nodes representing motor commands of the corresponding movements. Therefore, neurons in that network responded to both visual information and the corresponding motor commands. Learning of movements consisted of storing the movement sequences registered by the “visual” network and mapping them onto the motor commands of the M1 network. As such, the PM network simulated the functionality of the mirror-neuron system. This model was implemented on a biomechanical simulation of a human avatar, which managed to reproduce human movements with high level of accuracy. In [39], Mataric reported and summarized work devoted to the design of biologically-inspired imitation systems. The author described the main components of their models, i.e., the “visual and attention” system that detected and selected biological motion from a stream of visual input by focusing on effectors or tools; the system that mapped visual input onto motor programs (mirror-neuron system functionality); the motor control system consisting of motor primitives; and finally, a classification-based learning mechanism that learned “from a match between the observed and executable movements” and continuously expanded movement repertoire. These models have been implemented on artificial humanoid simulation avatars or robotic systems with high degree of success. Similarly, Breazeal and colleagues [40] provide an example of computational model inspired by the functionality of mirror neuron system as well as infant development and the idea of the Theory of Mind. Their robotic implementation of the model, Leonardo, is well capable of imitating facial expressions thanks to the architecture consisting of a perception system that extracts relevant features from the sensory data, for example, faces or its components such as eyes or lips, an action system that selects the appropriate behavior, and a motor system based on movement primitives. Importantly, Leonardo learns through imitation and interaction in a two-step manner. In the first phase, the human participant imitates Leonardo’s motor babbling – allowing Leonardo to map perceived human expressions onto its own intermodal representational space. The intermodal representations thus consist in learned correspondences between the model’s own expressions and those of the human imitator. In the second phase of imitative learning, once the robot has learned the representations of perceived facial expressions in intermodal space, it tries to imitate the human and optimizes imitation through successive approximations. Finally, the authors describe work in progress and future directions that would aim at equipping the robot with emotion and attention systems. These would allow for joint attention and emotional appraisal of novel situations, which in turn, are necessary for social referencing. Such skill is extremely important in social behavior, especially when it comes to understanding affective messages of others and emotional communication in general.

The above-described research is a prominent example how designing an artificial system based on results from human psychology and/or human/monkey neurophysiology might allow for establishing action understanding necessary for efficient human-robot interaction. In [41] Mataric describes how and why biologically-inspired architectures implemented in robotic platforms are important not only for theoretical but also for practical reasons. Mataric argues that humans have a tendency to “socially engage with, and attribute lifelike properties to machines, especially embodied ones such as robots, which exhibit sufficient (often quite simple) attributes of biological-like movement or appearance” (pg.82). This, in turn, leads to the possibility of designing artificial systems whose role is to provide care in hospitals, education and rehabilitation centers, programs for children with special needs and elderly people. Apart from the above arguments stressing the importance of implementing similar mechanisms in artificial systems to those that have developed in human or animal brains, drawing inspiration from nature might also be simply useful: for example, if humans have developed a fast pragmatic route of action-related selection [23] and if human perceptual mechanisms are biased towards action planning [5], [21], then designing systems that make use of such action-perception links might allow for solutions that are better tuned to their needs. The work of Cabibihan and colleagues [42] speaks in favour of this line of argumentation. The authors described a study in which they investigated a computer-based communication with social cues more rich than usual. That is, in contrast to standard internet-based communication such as Skype (Skype Technologies, Luxembourg), Cabibihan and colleagues developed a mobile robot interface capable of pointing gestures. The experimenter could communicate with the participants either using a standard static mode, i.e., through the notebook monitor positioned on top of the robot platform, or applying the dynamic mode, i.e., using the robot’s arms for pointing. The experimenter described to the participants a layout of items in commonly familiar places such as kitchen or living room. In the static condition, the experimenter used terms such as “left/right side of” or “behind”. In the dynamic condition, they used such words as “there” or “in that corner” and pointed to the respective directions with the robot arms. Subsequent to the communication session, participants were asked to recall positions of the items. Results showed that participants performed significantly better in the dynamic condition as compared to the static condition. The authors conclude that this might be thanks to that the dynamic condition involved a platform that was socially richer. Based on the argumentation put forward in this paper, an alternative interpretation might emerge: in the dynamic condition, due to interaction with the mobile platform and the pointing gestures, participants might have employed not the symbolic representation, but rather the action system in information encoding. Activating the action system, in turn, might have facilitated memory processes due to the action-perception links present in human cognitive architecture. In any case, this study is a prominent example showing that systems that make use of action-perception links might be more intuitive for humans and their usability might be simply better-tuned to the human needs.

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The Evaluation of Empathy, Autonomy and Touch to Inform the Design of an Environmental Monitoring Robot

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Abstract. This paper reports the application of results from human- social agent interaction experiments to inform the design of a social robot to monitor levels of pollutive gasses in the air. Next to licensed environmental agents and immobile chemical sensors, mobile technologies such as robotic agents are needed to collect complaints and smell descriptions from humans in urban industrial areas. These robots will interact with members of the public and ensure responsiveness and accuracy of responses. For robots to be accepted as representative environmental monitoring agents and for people to comply to robot instructions in the case of a calamity, social skills will be important. In this paper we will describe the intelligent environment the environmental robot is part of and discuss preliminary work on the effects of robot empathic and touch behaviors on human responses to robots. These and future findings will inform the design of social monitoring robot behaviors in public settings.

Keywords: Human Robot Interaction, Social robots, Environmental Monitoring, Robot Social Behaviors.

1 Introduction

In the future, virtual, mobile and physically embodied agents will function as part of distributed intelligent networks. In this paper we focus on a distributed intelligent network for environmental monitoring and the social robot that functions as the system's public interface. In urban-industrial areas, detection of chemicals (gasses) is important to monitor and control levels of environmental pollution. The environmental monitoring system DIADEM detects anomalies in air quality through dedicated electronic sensors and through complaints from the public. As anomalies are detected, an (semi-) autonomous system that in case of unusual sensor readings deploys a Bayesian reasoning system to reduce the number of possible events (e.g., which gas has been detected and whether it poses a threat). From that it will return a set of hypotheses (possible sources of pollution, for instance a factory or shipment in the harbor). If a potential hazard is detected, the system will call upon human observation in and around the affected area to gather more information. For this purpose, participating users will be requested by a mobile agent (through a remote mobile phone service or by autonomously mobile social robots) to self-report their observations, which are then

communicated to the central system. Exploiting smell perceptions from humans is promising [1], but also challenging, because although humans are very good at odor detection and discrimination, they are not good at odor identification and naming [2]. For developers of mobile applications designed for long-term environmental monitoring, it is crucial to establish and sustain a human-agent relationship. The aim is to motivate as many volunteer users as possible to quickly provide accurate and detailed information concerning observations about the environment over a long period of time.

If necessary, the system provides location-based warnings and safety instructions. The pollution detection context makes the relationship between humans and agent delicate. On the one hand, the system requires information from users to determine the likelihood and location of an incident. On the other hand, users would like to express concerns, complain about unfavorable smells, or receive instructions in the (unlikely) event of a hazardous incident. To inform the design of a mobile agent that will interact with members of the general public, a series of controlled experiments were carried out to assess the impact of several agent social behaviors on human responsiveness and accuracy of responses. In the following, we first present related work we consider relevant for studying human-robot interaction in field settings. Second, we present results of two studies that inform the design of the agent's social behaviors.

2 Related Work

Various research projects have highlighted the potential of context-aware and user adaptive applications for potentially high-risk and high-stress applications (e.g., disaster prediction and alerting [3]). Frequently, user-adaptive systems make decisions on behalf of the user, thus potentially leading to situations where users' perceive they are not in control of the system [4]. An overview of user-adaptivity issues, such as controllability, privacy, and transparency is provided by [5]. *Trust* is considered to be one of the important affective elements that play a role in human interaction with technology (e.g., [6]), and is crucially important in the environmental monitoring /crisis response domain tackled by this project. In addition, systems that display autonomous behavior will not simply be treated as tools; instead, users will interact with such systems as if they were social actors following social conventions, comparable to human-human interactions [7]. As illustrated by research into mobile persuasion [8], social and affective processes also play a role when interacting with mobile agents. Aspects such as perceived empathy with the user, actively acknowledging the user's (affective) experience, and acting accordingly could be key in achieving trust [9]. In a research project concerned with human-robot interaction in contexts where the information communicated is potentially of vital importance, establishing and maintaining a close social relationship between agent and user is crucial.

2.1 Trust in Robots

Appropriate social expressiveness appears to have great potential to instill trust and build relationships with users. Social expressiveness can for example promote liking, trust and perceptions that a system cares about the user [10]. Autonomous robots

could be present at any location and can provide (semi-) permanent connections to distant systems and services. They offer great potential for building long-term relationships where dialogues can be initiated by both users and systems at any time. Context-aware applications can provide users with services relevant to their current circumstances. Distant systems and services in turn can gather information from users and their devices about their surroundings (e.g. during a calamity). Such potential is accompanied by major challenges. These robots will make semi-autonomous decisions, request information and interrupt users' activities. We are not dealing with usage of robots as support tools anymore; instead we are presented with settings in which users collaborate with remote agents that also appear to have their own goals and intentions. These might differ from, or even conflict with, the current needs of the user. These systems will not simply be treated as tools; instead, users may interact with them following patterns from human social interaction [11]. Understanding what motivates people to collaborate with social robots in public spaces is an important focus of study.

2.2 Robot Empathy

Applying principles from social interaction has shown great potential, as illustrated by for example work on relational agents [10] and (mobile) persuasion [8]. Especially empathic system behavior has been suggested as a way to build relationships with users, increase trust and make interruptions more acceptable [9, 12]. Empathy has been gaining growing attention in the field as a very promising feature of user-system dialogues. Empathy combines social and affective aspects of interaction, it entails both the ability to accurately infer emotions and providing a supportive and compassionate response. Expressing empathy has been shown to for example lower user frustration and comfort users [10], increase users' liking, trust and perceived caring and support [9]. There are also indications it might alleviate the negative effects of interruptions [12]. A full overview of effects of social, empathic expressiveness however is not yet available. Reactions to social system behaviors can be affected by factors including users' task and (social) surroundings, the artifact they are interacting with, whether users actively reflect on the interaction and the specific social phenomena [13]. For human robot interaction, factors such as repeated (dis)engagement with the user system dialogue, proxemics and interacting with large autonomous technologies that have some antropomorph embodiment may also play a role. It is also unclear whether different effects exist in response when a social robot requests information from the user compared with giving more urgent system advice.

2.3 Robot Touch

The physical embodiment of robots makes it likely that humans will come into physical contact with them. Physical contact is an influential aspect of human encounters. Touch both influences and expresses interpersonal bonding; touch can communicate emotion, and can for example also decrease stress [14]. Physical contact can increase compliance with requests [15, 16], even when a person is not consciously aware physical contact has occurred [17]. Touch between humans and other living creatures can also have a profound effect on humans' affective state. Petting an animal for

example can decrease stress [18]. Touch and tactile qualities are also an important aspect of product design. Additionally, tactile interaction can offer possibilities for intuitive interaction with interactive products and systems, as explored in e.g. tangible interfaces [19]. Users might even expect interaction using touch when they encounter physically embodied agents. The accompanying potential for interacting with robots via affective touch has led to the development of robotic creatures that specifically aim to react to touch and/or offer haptic feedback. Haptic interaction with users is then implemented to achieve affective and social benefits especially in the context of therapeutic care, e.g. [20, 21]. However, humans will not only come into physical contact with robots specifically designed with affective touch capabilities. There are situations where physical contact might occur, ‘by accident’, or as part of social interaction, e.g. in human-robot collaborations (for instance consider a handshake, high five, pat on the shoulder, hug or elbow nudge).

Since physical contact is a very powerful and complex aspect of human communication, we should also consider how touch might influence interaction with physically embodied agents. Physical contact is not always considered appropriate behavior in every situation [14]. Personal preferences, cultural norms, familiarity, gender and social status all influence which physical distance is preferred in human interaction, how touch is experienced, how physical contact influences interactions and which types of tactile contact are considered appropriate ([14, 22], also noted by [21] and [23]). Given the importance of physical aspects of interaction between humans and the effects of touch on interpersonal bonds and e.g. compliance with requests, it is likely that physical contact will also have an impact on interaction between humans and physically embodied agents. What the effects of physical contact are on users’ perceptions and attitudes towards social agents is however unclear. The importance of determining the suitable physical distance, or ‘personal space’, that robots should keep from users during interaction has been highlighted by e.g. [24] and [23]. However, only limited attention has been given to the effects of physical contact. It is still unclear whether touch in interacting with robots will fully resemble effects in human interaction or interaction with other living creatures. Especially when systems behave in a more autonomous fashion it is likely that users will react to these systems in line with affective and social processes resembling human-human interaction [11]. However, Walters et al. [24] show that some users keep smaller physical distances from robots than from humans. Conversely, negative attitudes towards robots can also increase users’ preferred distance from robots [25]. It is unclear whether and when physical interaction might add to user trust and might be helpful in fulfilling social expectations. Studies into the effects of physical contact in combination with other social aspects of interaction are scarce as well. This, while the effects of touch also depend on social factors such as pre-existing bonds and attitudes towards other exhibited behaviors [14]. Research into the effects of physical contact with embodied agents is thus necessary especially when agents autonomously exhibit touch behaviors.

2.4 Robot Autonomy

When systems behave in a more autonomous fashion, social processes can play increasingly important roles [11]. We expect that the level of autonomy displayed by

embodied social agents will also influence how social and affective aspects of interaction, such as physical contact, are experienced. Perceiving others' needs and intentions and proactively acting on these perceptions are an important part of social interaction. Proactive agents that infer intentions from e.g. non-verbal, or contextual cues can potentially offer more intuitive collaboration with humans [26, 27]. System autonomy however has a tensive relationship with predictability and user control [28, 29]. Autonomous behavior and a loss of perceived user control can negatively influence attitudes and trust [30, 31]. Control is also crucial in maintaining combined human-system performance, e.g. in recovering from system mistakes [32]. The willingness to work with autonomous agents, or the willingness to delegate tasks to an agent depends on trust in the outcome of this collaboration [31]. In-depth studies on how combinations of social behaviors, such as touch and proactivity influence user perceptions and trust, are still relatively scarce. Kim and Hinds [33] have found that people attribute more responsibility to a robot for its behavior when the robot is more autonomous. This suggests that the effects of social behaviors such as touch and the perceptions of these behaviors as being (in)appropriate, could be amplified for more autonomous agents.

3 Evaluation of Robot Empathy, Autonomy and Touch

In order to gain more understanding in the responses that people have toward robot empathy, autonomy and touch, we have conducted two studies in the context of everyday usage rather than crisis response or environmental monitoring specifically [34, 35]. We hypothesized that robot's empathic behavior (understanding the situation of the user and responding accordingly) would lead to increased positive attitudes toward the robot. Apart from emotional empathy, the physicality of robots is important to take into account and we also felt that empathic touching behaviors by robots would lead to increased positive responses. However, it was unclear how robot autonomy would interact with such empathic robot behaviors. Highly autonomous robots may be seen as 'coming too close' once they start touching humans?

3.1 Study A: Effects of Empathy

A video-based, online survey experiment investigated participant' attitudes toward a four-minute interaction of a male user and a robot, playing an online collaborative game together [34] (for a discussion of validity of video-based methods, see e.g. [36]). The 2x3, between-subject experiment varied situational valence (negative vs. positive situation) and empathic accuracy (an empathically accurate, neutral agent and an empathically in-accurate agent), resulting in six randomly assigned conditions. The robot used in the resulting six videos was the Philips iCat, with a synthetic female voice. Data of 133 participants were analyzed (mean age 30.5, 53% male). Situational valence was manipulated by having the team do well on the collaborative game and win, or not do well together and lose. Empathic accuracy was varied using the robot's verbal responses and facial expressions. The robot's verbal and facial expressions in the empathically accurate condition were congruent to the situation (e.g. acknowledging a negative experience and looking sad when losing). In the neutral condition the

social robot made no statements about the person's affective state. In the empathically inaccurate condition, the robot's verbal and facial expressions were incongruent to the situation (e.g. looking happy when losing). Participants' (negative) attitude towards robots in general was measured using the NARS scale [10]. Likert-type and semantic differential scales were used to measure our dependent variables, including perceived empathic ability, trust (dependability, credibility) and closeness.

A significant interaction effect was found between empathic accuracy and emotional valence of the situation for the perceived empathic ability of the robot ($F(2,112)=4.326$, $p=.015$). Simple effects analysis showed a significant difference for empathy shown in a positive or negative context. In the 'winning' condition, participants rated the *empathically accurate* robot as having *greater empathic ability* compared with the empathically inaccurate robot, but this effect of accuracy was not significant ($F=1.18$, $p=.31$). However, when the team was 'losing' (negative context), participants found the *empathically inaccurate robot* to have *better empathic abilities* compared with the empathically accurate robot ($F=3.24$, $p=.043$).

A main effect was found for empathic accuracy of the robot on dependability ($F(2,106)=13.498$, $p<.001$). Planned contrasts showed that the neutral and accurate empathic robot were perceived as more dependable than the empathic inaccurate robot. The accurately empathic robot however was not perceived as significantly more dependable than the neutral robot.

The results confirm that inaccurate empathic behaviour can be detrimental to user attitudes toward a social robot. The findings also show that in a game setting, in a negative (losing the game) context, participants found the robot that responded inaccurately to have more empathic abilities. In short: When they were losing they found a positive robot more empathic even though its behavior was empathically inaccurate.

In the context of environmental monitoring in public spaces, robot empathy may play a different role compared with a collaborative game situation. A robot may need to be empathic when interrupting people and requesting smell descriptions, empathically respond to pollution complaints and related anxiety and so on. Therefore, it is unlikely that the findings from the study above can be generalised to an environmental monitoring context. However, a robot collecting responses from humans in public spaces clearly operates in an environment where empathy is necessary. If people indeed have less trust in robots that have inaccurate empathic responses, this could influence the reliability of the smell descriptions and public safety when the robots instructions are not heeded.

3.2 Study B: Effects of Touch and Autonomy

An online survey experiment was set up to explore how touch and autonomy influence perceptions of and attitudes toward robots [35]. The experiment investigated participants' responses to a video of an interaction between a user and a robotic assistant (WowWee Robosapien V2). The 2x2 experiment varied physical contact (touch, no touch) and robot autonomy (proactive, reactive behavior), resulting in four between-subject conditions. Participants were randomly assigned to one of the four conditions. To manipulate touch, the video in the touch condition showed four physical contact moments between the robot and user: the robot touched the user three times and the human touched the robot once. In the non-touch conditions, the robot

and user made no physical contact at all. The four touch behaviors were: the user tapping the robot at the beginning of the interaction, the robot tapping the shoulder of the user, the robot and the user sharing a hug, and a high-five between the user and robot at the end of the interaction. Proactiveness was manipulated by varying whether help was offered by the robot on its own initiative (proactive) or is offered on the user's request (reactive). In the proactive condition, the robot offered help without active prompting from the user, while in the reactive condition, the user asked for the robot's help. In total, 119 participants completed the survey-based experiment. 19 participants were female (16%), 100 were male (84%). Their average age was 25 years ($SD=6$). The majority of participants (80%) were Dutch. No differences were found between conditions on participants' gender, age, education level, computer and robot experience. Participants' (negative) attitude towards robots in general was measured using Nomura's 8-item NARS scale [25]. A dependent variable was trust in the robot. Items were measured on five or seven-point Likert-type scales ranging from strongly disagree to strongly agree.

Significant interaction effects were found for perceived trust ($F(1,118)=4.66$, $p=.033$). Analysis of the interaction effect on perceived trust showed that in the reactive condition touch influenced perceived trust ($F(1,116)=5.43$, $p=.022$), while in the proactive condition it did not ($F(1,116)=.24$, $p=.622$). In the reactive condition perceived trust was significantly higher for the non-touch version ($M=5.4$, $SD=.80$) than for the touch version ($M=4.6$, $SD=1.0$). In the proactive condition, the touch robot scored higher on perceived dependability ($M=4.90$, $SD=1.03$) than the non-touch robot ($M=4.8$, $SD=1.2$). However, this difference was not significant.

The results indicate that people trusted the proactive robot (higher autonomy) more when there was physical contact between the user and the robot. However, the reactive robot (lower autonomy) was trusted less when it engaged in physical interaction with the user. These findings show that robot touch behaviors do not necessarily lead to positive user responses, in this case it depended on the level of autonomy of the robot. The findings above suggest that people may be more comfortable touching a robot when it is more autonomous, particularly proactive. Even though the environmental monitoring context is very different from an office environment, this experiment indicates that robot proxemics may need to be designed carefully to optimise human trust in the robot.

4 Discussion and Conclusion

The results from our preliminary studies show that people's reaction to robot social behaviors such as empathy and touch are not unequivocal. Depending on the situational context or characteristics of the robot (e.g. level of autonomy), people's responses will vary. In study A, responses were more positive toward the robot that was empathically accurate. However when the human-robot team was losing, subjects were more positive toward the robot that responded inaccurately (i.e. 'we won! You look happy!'). Perhaps people prefer blind optimism in the face of adversity or experience the incongruence as humor. Future research should investigate this further but it is clear that complex social perceptions result from simple social robot behaviors. In the context of environmental monitoring, the emotional valence of a situation

can be very dynamic. When merely monitoring normal levels of pollution and gathering smell descriptions from humans, robots will not encounter users in high stress situations. However, when pollution is detected and smell descriptions from humans are necessary to determine the source and substance of pollution, human users may experience emotions such as stress and fear. It will be imperative for environmental monitoring agent robots to respond to users in such a manner to achieve high responsiveness and high accuracy of responses. In the case of an emergency, it is important that people comply with the robot's instructions. Accurate social behaviors to instill trust and credibility will be highly imperative.

The physical embodiment of the robot demands that we investigate what happens when humans and robots come into physical contact. In application areas where they will be in close proximity, such as environmental monitoring and calamity response, physical interaction whether intended or not, will happen.

The research in this paper stems from the notion that robots will provide services in public spaces in the near future. Next to functionality such as monitoring, providing information and cleaning, we envision such robots connected to intelligent monitoring networks for detecting aggression, pollution and so on. Since these agents will need to proactively interact with people in the public space it is unavoidable that people will experience this contact as social interaction. We have identified empathy, trust, autonomy and physical interaction as important aspects of human interaction with environmental monitoring agents in public spaces. Our future research efforts will focus on these issues and will evaluate human responses to robot behaviors in environmental monitoring contexts.

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Attention Determination for Social Robots Using Salient Region Detection

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Abstract. It is amazing that human beings can attend to the interest from a simple glimpse of scenes. Similarly, it is also important for social robots to determine its attention autonomously so as to behave human-likely and naturally. In this paper, we propose a technique to model this biological ability by searching saliency regions in a fast and reliable way. The salient regions are detected based on information entropy and biological color sensitivity. The information entropy evaluates the level of knowledge and energy contained, and the color sensitivity measures the biological stimulation to eyes of the presented scene. The performance of the detector is studied on natural scenes. The experiments proved the effectiveness of the detector and the important properties of invariance to transformation and illumination.

1 Introduction

Social Robots are currently weaving a hybrid society with human beings in everyday lives. They survive to keep in harmony with the environment and other individuals in social sense. It is hence significant for social robots to understand the circumstance in the similar way as human beings through the mounted cameras. Human beings can search and analyze complex scenes in a very fast and reliable way using visual attention according to the purpose and attraction. As computer vision algorithms are time consuming in the real robot applications, selection of interested regions and attention is usually employed in pre-processing.

Saliency region detection is widely researched in the field of computer vision. There are many different methods and techniques developed from insights of biology, information and perception. The earlier effort to solve the problem focuses on the properties of elements in the image such as points, lines and curvatures [1]. These kinds of methods can be useful for the scenes with apparent structures or images processed with edge detection methods. The popular feature extracted for saliency detection is the frequency distribution of the image

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with rich research effort. Spectral residual extracted by analyzing the spectrum can be used to map the saliency in frequency domain [2]. The superior of using phase spectrum over the amplitude spectrum has been shown in [3]. Phase Fourier Transformation performs well in searching the saliency locations, which is also easy to be extended to represent spatial-temporal saliency by covering sequential images. Salient feature extractor [4] and its affine invariant version [5] reveal the intrinsic relationship of salience, scale and contents. Moreover, they perform well in the selection of salient patches and their matches with adjustable parameters.

The detection of salient regions is crucial for social robots which determines the way social robots behaves in different scenarios. In the paper, we desire to endow social robots with biologically attention in scenes similar to human beings. We propose a detector searching saliency regions that attract the attention in the sense of color sensitivities and information, which is of important need especially for robot-environment interaction. Local information is employed to describe image contents. The advantage of this representation is relative invariance under transformation and illumination change. We focus on the impact of salient patches attracting human attention. The main contributions of this paper are highlighted as follows: (i) studying the sensitivities of human eyes to colors; (ii) proposing a saliency detector inspired by the biological eyes; (iii) investigating the performance of the proposed detector. The theory and implementation of the saliency detection for attention is discussed in detail in the following sections. In general, there are mainly two features to evaluate salient detectors: saliency and invariance. At the end of the paper, we show the experiments results and analyze the performance.

2 Attention Determination Using Salient Region Detection

In this section, we propose the approach to detect salient regions in a scene image. As introduced in Sect. 1, the saliency is defined in two senses: information entropy and biological color sensitivity. The color sensitivity measures the biological stimulation to eyes of the presented scene, and the information entropy evaluates the level of knowledge and energy contained. In this section, we first investigate the method to measure biological response of human beings to colors. The measurement of information is then proposed before the overall saliency criterion is presented.

2.1 Color Sensitivities

In different types of colorful scenes, social robots are expected to respond like human beings to color stimuli. Human eyes can sense the light ranging from red to violet, where red has the longest wavelength and violet the shortest. In fact, people can only detect the light with wavelength within 400^{nm} and 700^{nm} . The retinae of human eyes consist of two kinds of sensors named cones and rods. The

rods endow humans the ability of distinguishing the light intensity, and cones allow discriminating different colors. It is remarkable that the sensitivities of human eyes to colors are different. Human eyes are most sensitive to color green (550^{nm}) and yellow light (580^{nm}). The sensitivities of other colors decrease, such as sensitivity to magenta is 50% low and sensitivity to violet is 90% low. The diagram of sensitivities to each color spectrum is shown in Fig. 1a according to [6]. In the diagram, the lower arcs represent the sensitivities of the three kinds of cones with y-axis is the spectrum frequency. The luminous efficiencies of each individual tricolor sensor are severely different. There are various contributions of the low-wavelength-sensitivity (L), middle-wavelength-sensitive (M), and short-wavelength-sensitive (S) of cones. The curves represent the normalized response of an average human eye to color light with different wavelengths. From the experimental data, L- and M-cones play an overwhelming contribution of the overall sensitivity of eyes in comparison of that of S-cones. Hence, the contribution and pathway of S-cones are neglected in practical computation of luminance efficiency functions of biological vision research [7]. Consequently, the luminance efficiency function (LEF) follows the linear form of light wavelength

$$V(\lambda) = \frac{[\alpha L(\lambda) + M(\lambda)]}{\beta} \tag{1}$$

where $L(\lambda)$ and $M(\lambda)$ denote the luminous efficiency from L- and M-cone chromatic pathways with a and b are the scaling constants determined by the experimental results. A practical well-fitting configuration of parameters is $\alpha = 1.624340$ and $\beta = 2.525598$ and we adopt them in our experiments. This LEF reveals the relationship between eye sensitivities and light frequencies, and the attractiveness features of colors as shown in Fig. 1b.

With the merit of this biology research, we are able to quantitate the degree of color attraction. As the luminous efficiency function takes the wavelength as the arguments, the pixel colors of a scene image need to convert to corresponding

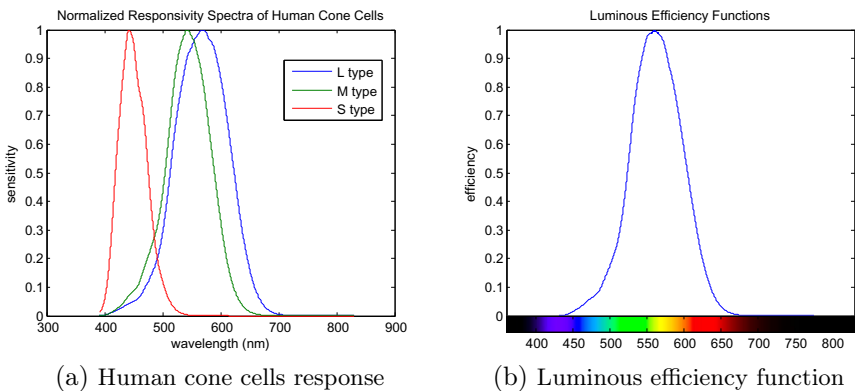


Fig. 1. Human eye's response to lights

wavelength or frequencies. Unfortunately, given a scene image of RGB format, there is no physically possible mapping from a color to corresponding light wavelength in that RGB gamut and spectrum locus do not intersect. However, the dominant wavelength λ of a color can be achieved by virtue of CIE chromaticity diagram shown in Fig. 2. The dominant wavelength of a color is monochromatic light that generates the same saturation and hue in the presence of the illuminant source. In the chromatic diagram, the boundary line represents the chromaticity of spectral colors. The dominant wavelength of a color is determined by the interaction of the spectrum locus and the straight line that passes the illumination (the white point in the diagram) and color point. When the color point falls into the purple region, the complementary dominant wavelength is given by the interaction which is in the reverse side of that line. It is worth noting that the color in the chromatic diagram is described in chromaticity coordinates. A color space conversion from $sRGB$ to XYZ needs to be performed. In Sect. 2.3, we will discuss the way to apply this measurement in detail.

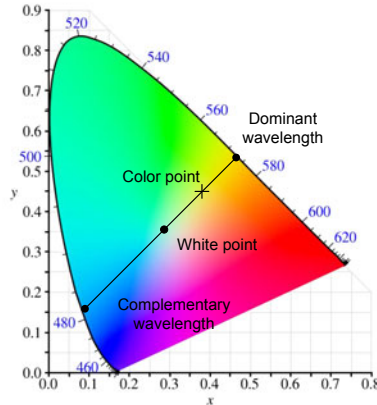


Fig. 2. Color matching diagram (The CIE 1931 color space chromaticity diagram. The outer curved boundary is the spectral or monochromatic locus, with wavelengths shown in nanometers.)

2.2 Illumination Entropy

The other feature we try to simulate for social robots is the ability to find the regions with most information. In the information theory, the concept of entropy developed by Shannon measures the extent to which a system is organized or disorganized. Entropy is being popularly applied as a measurement in many fields of science including biology, mechanics, economics, etc. In this paper, we employ entropy measurement to represent the scale of saliency in a single region. The rationality lies on the fact that salient parts usually convey much information. The salient detector proposed in [4] shows good performance in detecting and matching of found salient regions. That detector, however, consumes the computation resources and salient regions found out are most locally.

To compute the illumination entropy, the probabilistic distribution of illumination in the image needs to be obtained. For a natural scene image, a prior knowledge of the distribution of the illumination is usually not available [8]. It is possible, however, to estimate the density function from the given image data. Currently, the estimation approach of color distribution based on histogram covers annular color histogram, spatial-chromatic histogram and Geostat [9]. Both of the latter two methods need calculation of the distance of each other point that causes much computation burden. In this paper, we hence propose a weighted annular color histogram (WACH) to estimate the distribution density, which can also confine the region size to be reasonable after introducing the weights.

The illumination image $I(x, y) \in \mathbb{R}^{X \times Y}$ with size (X, Y) is achieved by converting the color scene image into the grayscale space. The candidate region $R(c, r)$ is divided uniformly into N circular sub-regions $R_i, i = 1, 2, 3 \dots$ with common center c and the radii $r_i = n \frac{r}{N}, 1 \leq n \leq N$. In Fig. 3, the set of illumination pixels in R_i within color bin j of the image is denoted as R_i^j , and $|R_i^j|$ represents the number of the pixels. The illumination histogram for this can hence be achieved as $(|R_i^j|)_{i=1}^N$. Based on these illumination histograms, the distribution density of the image illumination is defined as

$$\Pr(R^j) = [\Pr(R_1^j), \Pr(R_2^j), \dots, \Pr(R_N^j)]^T \tag{2}$$

where $\Pr(R_i^j) = \frac{|R_i^j|}{\sum_{i=1}^K |R_i^j|}$ is normalized distribution. With this estimated illumination distribution, the illumination entropy in this region is measured by

$$E(R) = - \sum_{j=1}^K \sum_{i=1}^N \Pr(R_i^j) \ln \Pr(R_i^j) \tag{3}$$

where K is the total number of illuminations in the image. Similarly to the definition of entropy, this measurement presents the degree of pixel distributes and the spatial information of illuminations in that patch. The larger the $E(R)$ is, the more the information is in this region, and the more attractive this region is. The illumination entropy in (3) is prone to increase the candidate salient region. To keep the size of salient regions reasonable and meaningful, the estimated illumination distributions are weighted with

$$E(R) = - \sum_{j=1}^K \sum_{i=1}^N w_i \Pr(R_i^j) \ln \Pr(R_i^j) \tag{4}$$

The distribution densities of the image illumination estimated are influenced by the size of the patch, although each of the patches is normalized. An effective solution is using different weights to assure that the central partitions are with high priority. One of the simple functions to set the weights w_i is truncated Gaussian distribution $\mathcal{N}(\mu, \sigma)$. The illustration of the annual color histogram

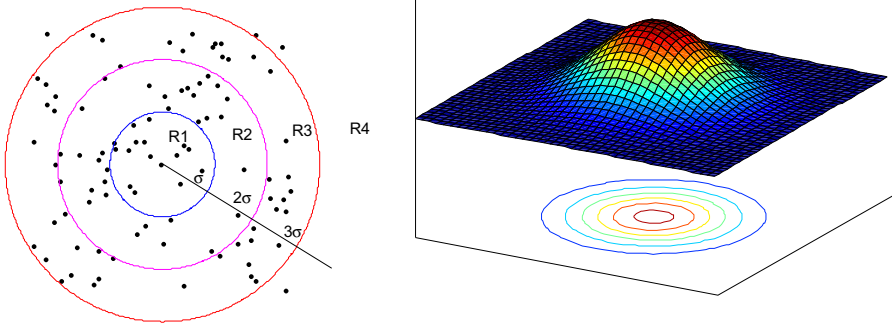


Fig. 3. Weighted annular color histogram

with this weight function is shown in Fig. 3. The radii of the salient regions are selected as the variance σ . According to the feature of Normal Distribution, around 68% of values drawn from the distribution are within the range $[\mu - \sigma, \mu + \sigma]$, and there are nearly no random instances fall out of $[\mu - 4\sigma, \mu + 4\sigma]$. From the definition of the weighted saliency, the conclusion can be drawn that the born merit of the illumination measurement proposed in this section is the rotation invariance.

2.3 Saliency Detector

The fundamental problem of saliency detection is to determine the location and the size of the salient region. Since we have investigated the measurement of color sensitivities and the amount of information, the regions can be determined where information entropy and biological color sensitivity are maximized. Given a scene image region, the judgment criterion is given by

$$J(R) = - \sum_{j=1}^K \sum_{i=1}^N w_i \Pr(R_i^j) \ln \Pr(R_i^j) + \frac{1}{N} \sum_{i=1}^N \sum_{C^{rgb} \in R_i} \frac{1}{|R_i|} V(g(C^{rgb})) \quad (5)$$

where $\lambda = g(C^{rgb})$ is the function to obtain dominant wavelength from RGB color $C^{rgb} = [r \ g \ b]^T$ according to Fig. 2. As $R(c, r)$ is determined by the location and size, we desire to find the optimized size configuration with $r^* = \arg \max_r J(R(c, r))$. For continuous functions, this can be solved by computing

the stationary points satisfy $r : \begin{cases} \frac{\partial J(R(c, r))}{\partial r} = 0 \\ \frac{\partial^2 J(R(c, r))}{\partial r^2} < 0 \end{cases}$. However, there is no closed

form relation of $J(R)$ and (c, r) . We hence propose to use the discrete search algorithm to achieve the local optimal solution of (5). The algorithm is presented in Algorithm 1.

Algorithm 1. Saliency detector

Require: Determine the radius step length h and the saliency criterion threshold J_{th}

- 1: **for all** pixel $c^{(i)}$ in the scene image **do**
- 2: **for all** sampled radius $r^{(k)} \in [r_{min}, r_{max}]$ **do**
- 3: Estimate the illumination distribution according to (2)
- 4: Compute saliency criterion using (5)
- 5: Let $J^{(i)(k)} = J(R(c^{(i)}, r^{(k)}))$
- 6: Compute first derivative $\frac{\partial J^{(i)(k)}[k]}{\partial r} \approx$

$$\frac{-J^{(i)(k+2)} + 8J^{(i)(k+1)} - 8J^{(i)(k-1)} + J^{(i)(k-2)}}{12h}$$
- 7: Compute second derivative $\frac{\partial^2 J^{(i)(k)}[k]}{\partial r^2} \approx$

$$\frac{-J^{(i)(k+2)} + 16J^{(i)(k+1)} - 30J^{(i)(k)} + 16J^{(i)(k-1)} - J^{(i)(k-2)}}{12h^2}$$
- 8: **if** $\frac{\partial J^{(i)(k)}[k]}{\partial r} \approx 0$, $\frac{\partial^2 J^{(i)(k)}[k]}{\partial r^2} < 0$, and $J > J_{th}$ **then**
- 9: Update salient region list
- 10: Continue to next pixel $c^{(i+1)}$
- 11: **end if**
- 12: Increase radius $r^{(k+1)} \leftarrow r^{(k)} + h$
- 13: **end for**
- 14: **end for**
- 15: Optimize the salient regions by reducing the redundant ones

3 Experiment and Analysis

In this section, the performance of the proposed salient detector is evaluated by showing the results of attention regions with different numbers of salient regions, studying the common attention direction of the social robots in various scene images, and investigating the invariance of the detector to light and view point. In the experiments, the data images are collected from photos of the university and the image database LabelMe.

3.1 Attention Selection

For a group of images, we applied our saliency detector to find the regions attracting attention. The results are shown in Fig. 4. The images are normalized into 640×480 , and parameters of the detector are set as $r_{min} = 10$, $r_{max} = 40$. To investigate the influence on the attention regions by the number of salient threshold J_{th} , the attention regions are compared in the diagram from the left column to right ones as J_{th} decreases. From the results, it is proved the algorithm can find the salient regions with more information and attraction.

3.2 Invariance to Light and View Point Change

The most significant purpose of salient detectors is finding the meaningful regions that attract attention. We have conducted this evaluation in the previous

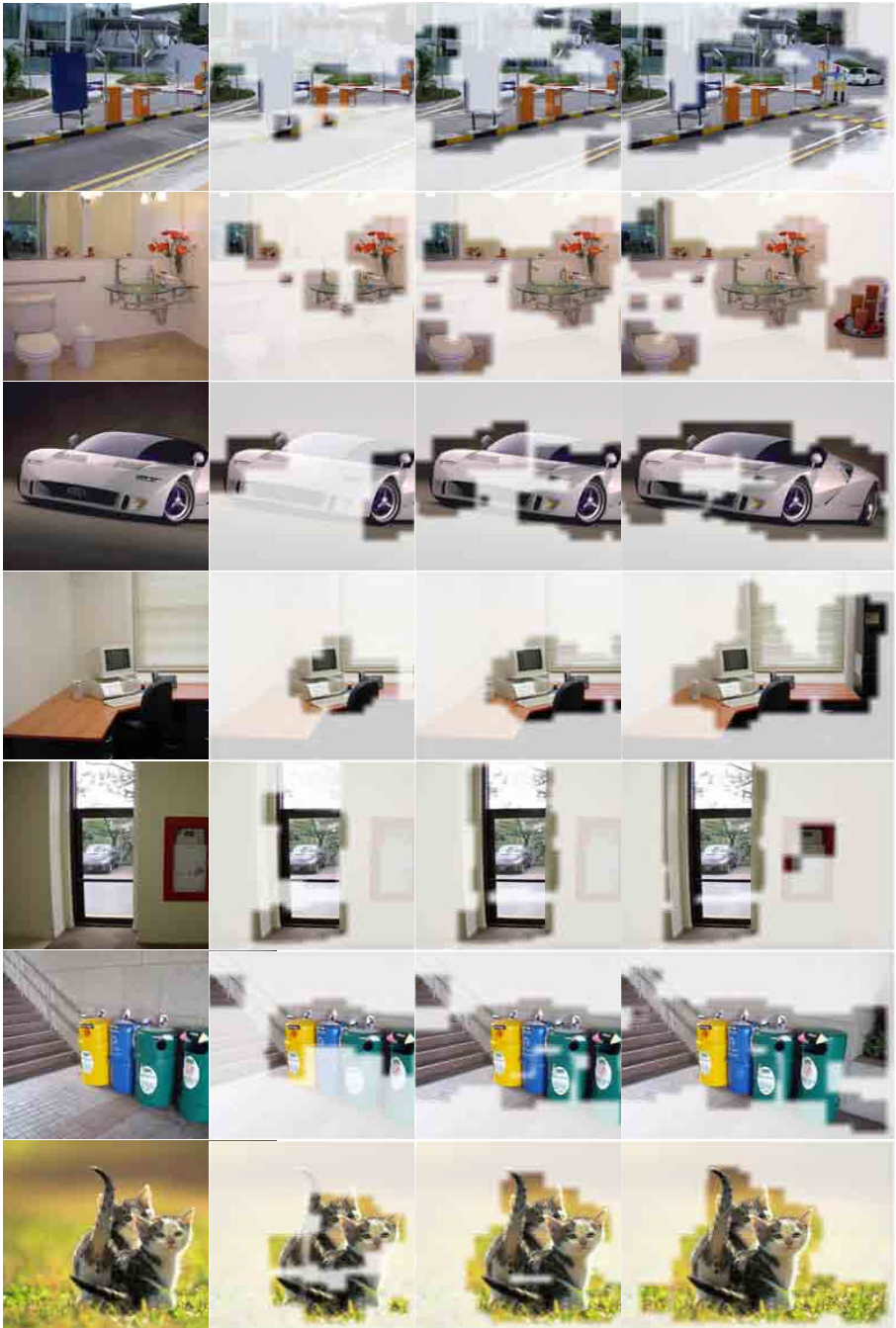


Fig. 4. Attention selection by saliency detecting (the number of saliency regions increases from the left column to the right one)

section. In this section, we study the stability of the detector subjected to the variance of view point and light. The matching error is measured by computing the percentage of overlapping salient areas. In Fig. 5, the left diagram shows the influence of the detecting results whilst the light is adjusted, and the right diagram presents the performance of the detector under the change of view point. From the figure, it is easy to draw the conclusion that the matching errors increase as the disturbance of light and viewpoint grows. However, the greatest average error is around 10%, which guarantees the reliability of salient regions with different external conditions.

3.3 Common Attention Direction

In everyday lives, people are accustomed to search certain regions which are related to the types of the scene. To study the most common attentions of the social robots within different scenes, the popular attention regions of four types of scene images are compared in Fig. 6. The attention images are obtained by average a sequence of scenes attentions within the same scene detected by

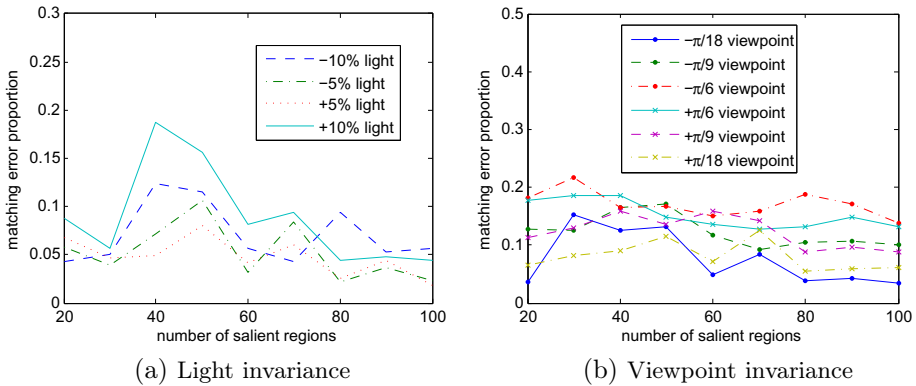


Fig. 5. Invariance performance

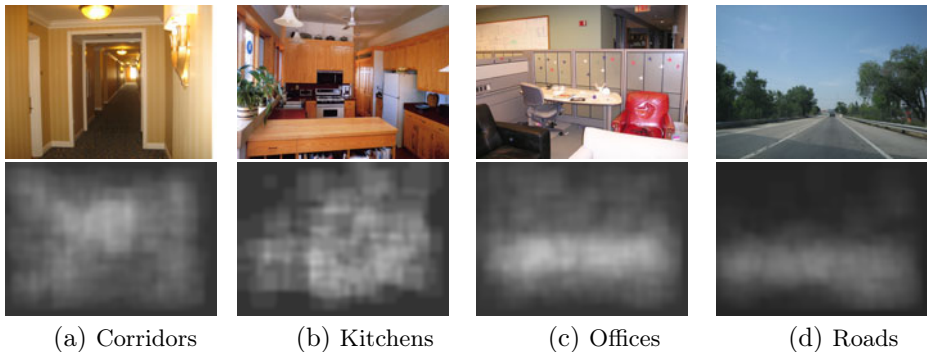


Fig. 6. Most popular attention regions of different scenes

the proposed method. From the diagram, it can be concluded that there are specific patterns of saliency detecting for a class of scenes. The focus of corridor scenes is, for instance, usually in the middle of the way, and the ones of outdoor scenes are frequently dispersed in the whole view. The average results prove the effectiveness of the proposed method in simulating the biological visual behaviors of human beings.

4 Conclusion

In this paper, we proposed a salient region detector that helps social robots determine the attention in a scene. The technique finds the regions according to information entropy and biological color sensitivity that mimic the tenderness of information and biological stimulation of light. The presented technique succeeds to simulate the biological response to natural scenes. Through the experiments, the detector shows good performance on invariance to image transformation and the stability of the detecting results. This demonstrates the effectiveness of detecting attractive regions to assistant social robots in determining attention.

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Bimodal Emotion Recognition

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Abstract. When interacting with robots we show a plethora of affective reactions typical of natural communications. Indeed, emotions are embedded on our communications and represent a predominant communication channel to convey relevant, high impact, information. In recent years more and more researchers have tried to exploit this channel for human robot (HRI) and human computer interactions (HCI). Two key abilities are needed for this purpose: the ability to display emotions and the ability to automatically recognize them. In this work we present our system for the computer based automatic recognition of emotions and the new results we obtained on a small dataset of quasi unconstrained emotional videos extracted from TV series and movies. The results are encouraging showing a recognition rate of about 74%.

Keywords: Emotion recognition; facial expressions; vocal expressions; prosody; affective computing; HRI.

1 Introduction

The abilities to recognize, process, and display emotions are well known to be central to human intelligence, in particular influencing abilities such as communications, decision making, memory, and perception [3]. In recent years more and more researchers in the human computer (HCI) and human robot interactions (HRI) societies have been investigating ways to replicate such a kind of functions with computer software [6, 13, 18]. In our domain, emotions could be used in many ways but two in particular are more relevant: 1) emotional communications for HRI [14], and 2) decision making for autonomous robots [5].

One of the key abilities of these systems is the ability to recognize emotions. The state of the art is rich with systems performing this task analyzing people's facial expressions and/or vocal prosody (see [18] for a thorough review). One of the main limitations of most of existing technologies is that they only have been tested on very constrained environments with acted emotions.

In this work we want to present our last results toward the development of a multimodal, person independent, emotion recognition software of this kind. We have tested our system on less constrained data in the form of movies and TV series video excerpts. The results we present are very promising and show that even in these almost unconstrained conditions, our system could perform well allowing to correctly identify as much as 74% of the presented emotions.

2 Multimodal Approach

In our approach we are targeting the identification of seven different emotions¹ by fusing information coming from both the visual and the auditory modalities.

The idea of using more than one modality arises from two main observations: 1) when one, or the other, modality is not available (e.g. the subject is silent or hidden from the camera) the system will still be able to return an emotional estimation thanks to the other one and 2) when both modalities are available, the diversity and complementarity of the information, should couple with an improvement on the general performances of the system.

Facial Expression Features. We have developed a system performing real time, user independent, emotional facial expression recognition from video sequences and still pictures [10,12]. In order to satisfy the computational time constraints required for real-time we developed a feature point tracking technology based on very efficient algorithms.

In a first phase, the face of the subjects in the video is automatically detected thanks to a slightly modified Viola-Jones face detector [17]. When the face is detected twelve regions are identified thanks to an anthropometric two dimensional mask similarly to what it is done by Sohail and Bhattacharya in [15]. Then, for each region of the face, we apply the Lucas-Kanade [16] algorithm to track a cloud of keypoints. Finally, the positions of these points are averaged to find one single center of mass per each region (see figure 1(a)). We call the set of the x and y coordinates of these 12 points *coordinates* feature set.

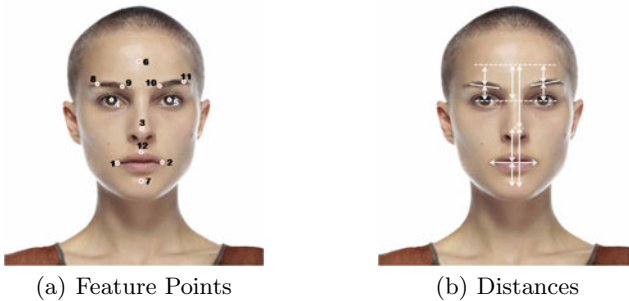


Fig. 1. Video Features

As a second step we have extracted a more compacted feature set in a similar way to the one adopted by MPEG-4 Face Definition Parameters (FDPs) and Face Animation Parameters (FAPs). This process resulted in 11 features defined as distances and alignments $distance(j)$ from the keypoints in the *coordinates* feature set (see figure 1(b)). Additionally we explicitly keep track, in this feature

¹ The six “universal” emotions listed by Ekman and Friesen [4] (i.e. anger, disgust, fear, happiness, sadness, and fear) and the neutral state.

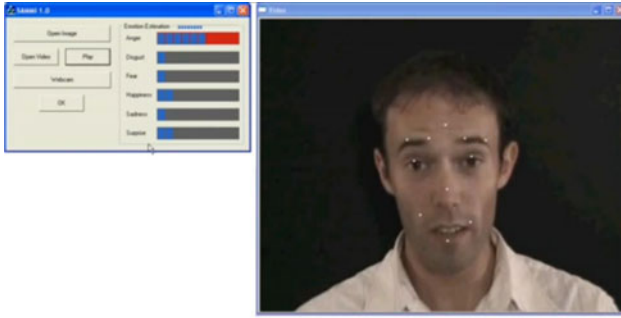


Fig. 2. Emotion Recognition System Interface

set, of the x and y displacement of the face and of a zooming factor (which is proportional to the z displacement). We refer to this set of distances, alignments, and displacements as to the *distances* feature set.

Prosodic Expression Features. Our system for speech emotion recognition, takes deep inspiration from the work of Noble [8]. From the audio signal we extract: the fundamental frequency (pitch), the energy, the first three formants, the harmonicity (a.k.a. harmonics to noise ratio), the first 10 linear predictive coding coefficients (LPC), and the first ten mel-frequency cepstral coefficients (MFCC).

These 26 features are collected with the use of PRAAT² [1] and downsampled to 25 samples per second to help synchronization with the video features.

3 Emotion Recognition System

In the former section, we overviewed the modality of extraction of audio and video features. In this section, we detail the other procedures defining our emotion recognition system (see figure 2).

To evaluate this system we employ three measures: the recognition rate of the positive samples $CR_i^+ = \frac{\text{well_tagged_samples_of_emo}_i}{\text{samples_of_emo}_i}$, the average recognition rate $m(CR^+) = \frac{\sum \text{well_tagged_samples_of_emo}_i}{\text{samples}}$, and the weighted standard deviation $wstd(CR^+) = \frac{std(CR^+)}{m(CR^+)}$ ³. The objective of our recognition system would be to maximize the $m(CR^+)$ while also minimizing the weighted standard deviation $wstd(CR^+)$.

For this experiment we have trained three different neural networks per each one of the six universal emotions using data from the audio, the coordinates, and the distances feature sets respectively.

² PRAAT is a C++ toolkit written by P. Boersma and D. Weenink to record, process, and save audio signals and parameters. See [1].

³ $wstd$ will be low if all emotions are recognized with the same likelihood and vice versa if some emotions are much better recognized than others, it will be high.

It is important to notice that not all of the *audio*, *coordinates*, and *distances* features are used for all emotions. In [12] we presented a work in which we compare singularly each one of the $64 = 24 + 14 + 26$ features we have presented in sections 2 for the recognition of each one of the six “universal” emotions. As a result of this study we were able to select the best features and processing for recognizing each one of the selected emotions.

In table 1 we list the features which have been selected for this study.

Table 1. Selected features for the different emotions

Emotion	Audio features	Coordinate features	Distances features
Anger	Energy, Pitch, & HNR	Eye Region	Head Displacements
Disgust	LPC Coefficients	Eye Region	Eye Region
Fear	MFCC Coefficients	Eye Region	Head Displacements
Happiness	Energy, Pitch, & HNR	Mouth Region	Mouth Region & x Displacement
Sadness	LPC Coefficients	Mouth Region	Mouth Region
Surprise	Formants	Mouth Region	Mouth Region

In a first phase we have evaluated this setup on a publicly available multimodal database. We have employed neural-networks with one hidden layer composed of 50 neurons which have been trained on a training set composed of 40 randomly selected subjects from the eNTERFACE’05 database [7]. The extracted data was fed to the networks for a maximum of 50 times (epochs). The remaining 4 subjects were used for test (the database contains videos of 44 subjects acting the 6 universal emotions). We have repeated these operations 3 times (as in an incomplete 11-fold cross validation) using different subjects for test and training and averaged the results.

Then, the outputs of the 18 resulting neural-networks have been filtered with a 25 frames low-pass filter to reduce the speed in which the output can change; indeed, emotions do not change at a speed of 25 frames per second. This filtering shall also improve the results as discussed in [11].

For each emotion, we have employed a Bayesian approach to extract a single multimodal emotion estimate per frame o_{emo} . The Bayesian approach has been preferred to other simple decision level fusion approaches and more complex ones such as the NNET approach [9] as one returning very good results without requiring any training. The resulting system could recognize an average of 45.3% of the samples, $wstd(CR^+) = 0.73$.

The reasons why the $wstd$ is so high is because of the statistics of the outputs for the six Bayesian emotional detectors are very different. Therefore, we computed the minimum, maximum, average, and standard deviation values for each one of the detector outputs and proceeded to normalize the outputs to have a minimum estimate equal to 0 and a similar average value.

Performing this operation raise the $m(CR^+)$ to 50.3% while decreasing the $wstd(CR^+)$ to 0.19. In figure 3(a) we can see the CR^+ for the six different emotions after this phase of normalization.

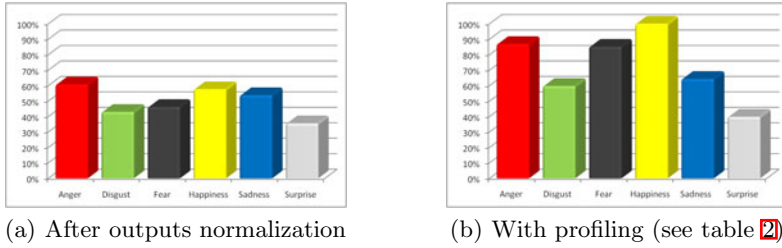


Fig. 3. CR^+ results

To further boost the results we apply a double thresholding strategy to these results. Firstly, we define a *threshold* below which results are not accepted because they are evaluated as being not reliable enough.

Secondly, we apply a function which we called inverse thresholding. In this case, we select more than one estimates for the same audio–video frame in the case in which two (or more) detector outputs are both above a certain $threshold^{-1}$. This operation is somehow similar to using a K–best approach but in this case more estimates are selected only when they are “needed”.

Thresholds are defined as a function of the output mean and standard deviation values making the assumption that the distributions of the outputs of the detectors are Gaussians. We call the phase of choosing an appropriate couple of thresholds *profiling*. By choosing different profiles the system act differently and its behavior can be dynamically adapted to its specific needs.

It is interesting to note that infinite profiles can be defined which returns about the same number of estimations. Indeed, increasing the threshold or decreasing the inverse threshold have opposite influences on the number of estimations.

In table 2, we compare two possible profiling setting together with the originated results.

Table 2. Selected features for the different emotions

#	Recall	Thresholding Value	Inverse Thresholding Value	$m(CR^+)$	$wstd(CR^+)$
0	100%	0	1	50.3%	0.19
1	49.7%	$m(o_{emo}) + 1.2 * std(o_{emo})$	$m(o_{emo}) + 2.0 * std(o_{emo})$	61.1%	0.29
2	12.9%	$m(o_{emo}) + 3.0 * std(o_{emo})$	$m(o_{emo}) + 5.0 * std(o_{emo})$	74.9%	0.29

As expected, the two systems maintain low weighted standard deviation values while improving the mean recognition rate of the positive samples.

4 Relaxing Constraints

In the former sections we have introduced the topic of emotion recognition for human machine interactions (HMI) and overviewed our multimodal, person independent system. In this section we aim at relaxing the constraints to see how the system behaves in more realistic conditions.



Fig. 4. Screenshots from the excerpts database

To perform this task we have collected 107 short (4.2 ± 2.6 seconds) DivX quality excerpts from three TV series, namely “The Fringe”, “How I met your mother”, and “The OC” and the Joe Wright’s 2007 movie “Atonement” (see figure 4). The video sequences were selected to represent character(s) continuously in a shot longer than 1 second. It was required for at least one character to roughly face the camera along the whole video.

The result is a set of videos with very heterogeneous characteristics; for the visual modality we observe:

- more than one subject on the same video
- different ethnic groups
- different illumination conditions: non uniform lightening, dark images ...
- different gaze directions
- presence of camera effects: zoom, pan, fade ...

Also the auditory modality presents lesser constraints and in particular we have samples with:

- different languages (i.e. Italian and English)
- presence of ambient noise
- presence of ambient music
- presence of off-camera speech

4.1 Evaluation

Each one of these video is being evaluated thanks to an online survey on YouTube⁴. We asked several subjects to tag the excerpts in the database with one (or more) of our 6 emotional categories; the neutral tag was added to this short list allowing

⁴ http://www.youtube.com/view_play_list?p=4924EA44ABD59031



Fig. 5. Distribution of human tags

in \ out	ANG	DIS	FEA	HAP	SAD	SUR
Anger	13%	17%	10%	20%	17%	13%
Disgust	28%	0%	22%	6%	28%	17%
Fear	10%	13%	3%	26%	22%	26%
Happiness	17%	3%	23%	6%	20%	31%
Sadness	20%	12%	17%	17%	12%	22%
Surprise	11%	9%	23%	31%	26%	0%

Fig. 6. Correlation matrix of human tags

people to tag non emotional relevant excerpts. We currently have collected about 530 tags (4.99 ± 1.52 tags per video); each video segment has been evaluated by a minimum of 3 different subjects.

Few subjects decided to tag the videos only using audio or video but most exploited both modalities trying to understand what the emotional meaning of the characters in the video was. In average, every video was tagged with 2.2 different emotional tags but usually a tag is identifiable which was hit by over 70% of the subjects of our online survey. In 10 cases agreement on a single tag representing an excerpt could not pass the 50% threshold; in 8 of these cases neutral is among the emotions that are most indexed by our online survey, justifying the confusion. The remaining segments are tagged as representing two different emotions: a first one is represented by anger and surprise, the second by sadness and disgust. It is interesting to notice that, the emotions belonging to both couples have adjacent positioning on the Valence Arousal plane thus justifying, in part, the confusion among the two.

Figure 5 reports the distribution of the tags. As it can be observed the emotion neutral is predominant to the others representing about 40% of the tags that the subjects of our survey employed.

Sadness is the most common emotion in our database (with 16% tags), disgust is the emotion which is less identified by our online survey: only 3% of the tags human gave belong to this emotion.

Table 6 report the correlation matrix of the human tag. Each cell in the tab contains the percentage of videos of the emotion identified by the row which are also tagged as belonging to the emotion in column. As it appears in table 6 the emotions presented in the videos may be easily confused with each other. We identified 6 main reasons which can justify this result:

1. in films and TV series emotions tend to be complex mixes of emotions;
2. the excerpts are, for their very nature, extrapolated from the context; without it people are not always able to correctly recognize the expression;
3. the emotion presented could not always fit well into one of our categories;
4. in most cases the presented emotions are not characterized by high intensity, thus being confused with neutral states and similar emotions;
5. in some cases social norms makes character hide their emotional state possibly distorting or hiding the emotional message;

6. in some cases the intention of the director is to convey an emotion different to the one of the character being depicted: this emotion may be transferred by other means such as music, colors, etc. and influence the human perception.

4.2 Results

As it was pointed out in the former section, our online survey led most video excerpts to present two or more emotional tags.

Given the different characteristics of the train and test database (specifically the fact of presenting or not multiple emotional tags per video) a new metric needed to be defined. We decided that if an emotion is tagged by someone than it is reasonable to say that when a computer returned the same tag it did not make an error. With this idea in mind, without modifying the system described in section 3, and by applying the second profile from table 2, we analyzed audio and video of the multimedia excerpts of the newly designed emotional database.

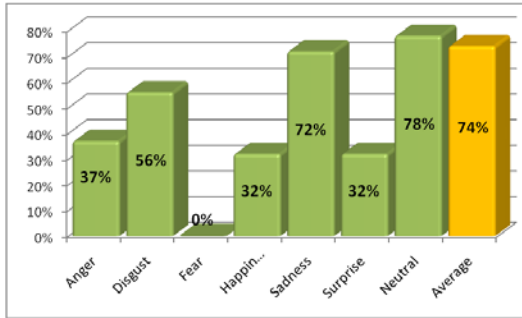


Fig. 7. Recognition rate on real videos

Figure 7 reports the result obtained by this system. The resulting average recognition rate on six emotions is of about 44% but it is boosted to 74% ($wstd = 0.36$) if neutral is considered as a seventh emotion. Please note that the number of frames tagged by our online survey as being neutral is about 6 times higher than the number of frames belonging to all the other emotions. Please also note that also considering the emotion neutral in the metric brings the recall rate back to 1: all frames are evaluated as belonging to one emotion or neutral.

Given the relatively small size of the employed database it may be normal for some emotions to be worse recognized than average (please note fear has only 5 samples). Nevertheless, it is important to comment the disappointing result obtained for the emotion “fear” and the very good one returned for “sadness”.

Our analysis of the data suggested that the result obtained for “fear” may be explained with the differences underlying the emotional excerpts of this real-video database and our original train base. Analyzing the videos we noticed that the videos of the eINTERFACE database depicted some kind of surprisedly

scared emotion while in our new database the emotion depicted is often similar to some kind of cognitive and cold fear. In other words, it is our conclusion that while both the emotion represented in the eNTERFACE database and the one represented in our test database are definable as fear, those two kind of emotions are different, e.g. they arise from different appraisals, and therefore have different expressions.

A similar behavior might as well have deteriorated the performances of the emotion anger; we know, indeed, that there are at least two kind of anger, namely “hot” and “cold”.

Nevertheless, it is important to notice that, as a whole, the average recognition result clearly shows that without any modification or adaptation the system described here can work for emotion recognition of multimedia excerpts and it is likely to work on real scenarios too.

5 Concluding Remarks

In this paper, we have discussed the topic of multimodal emotion recognition and, in particular, a system performing bimodal audio–visual emotion recognition has been presented. Many different scenarios for human–robot interaction and human-centered computing will profit from such ability.

Our emotion recognition system has been presented and we have discussed the idea of thresholding, inverse thresholding, and profiling. The system is able to recognize about 75% of the emotions presented by the eNTERFACE’05 database at an average rate of more than 3 estimates per second.

Finally, we have shown the results obtained by this system on quasi unconstrained video conditions. For this study, an experimental database of 107 real video sequences from three TV series and a movie were extracted. The results on this small dataset confirm that our system works for the detection of emotions in real video sequences. In particular, we have showed that with the current setup the system could correctly tag as much as 74% of the frames (when considering neutral as a seventh emotion).

Because of the size of the database and number of tags, the metric we applied can be considered good, but different metrics shall be considered in the case in which many more tags were to be available; in particular we selected two: the first one only considers the most common human tag as the corrected one, the second weights the correctness of the computer outputs by the percentage of given human tags. With these two metrics the system performs 55% and 39% respectively.

Ongoing work consists in increasing the size of this database to extract more results. Future work will focus on the idea, developed in [2], of separating the frames of the video shots into two classes of silence/non silence frames to apply different processing; furthermore, we are trying to extend this idea by introducing a third and a fourth classes representing music frames and frames in which the voice does not belong to the depicted characters.

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Objective Evaluation of Spatial Information Acquisition Using a Visuo-tactile Sensory Substitution Device

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Abstract. This paper proposes a method to objectively assess the degree of sensory transfer in a visuo-tactile Sensory Substitution task. Using a special purpose single taxel-based device, users discover with tact some virtual objects of increasing geometrical complexity, while EEG signals are recorded. Successful reconstruction, as well as cognitive load and brain programming, are found to be associated with relative activation/deactivation of specific EEG bands, and to the users' exploration strategies, which allows us to objectively assess the perceived degree of complexity of the reconstruction task. Our metrics also provide an evaluation tool for the design of devices useful for the navigation of visually impaired people.

Keywords: sensory substitution, tactile interface, virtual reality, neurophysiology, EEG, telerobotics.

1 Introduction

The central problem of *Tele-robotics* is to provide effective tools allowing to humans to perform physical modifications of distant environments. In such a context, tele-robots have to capture users motor controls and translate it into remote robots commands. On the other hand, tele-robots acquire data through embedded sensors and build a remote environment description to be displayed to operators. This closed-loop control scheme is mainly supported by bilateral interfaces. These latter convey sensory-motor information between the two partners. Unfortunately, these interfaces are known to distort and to reduce information flows: the operator has a partial and incorrect knowledge concerning the remote world status. As well, all operator's actions and motor intents are not fully taken into account. As a dual system, the tele-robot is in fact inherently asymmetric because humans and robots belong to two different sensory-motor spaces. This situation can be easily extended to more generic contexts where humans interact with or through machines.

Our work is dealing with an extreme situation of sensory asymmetry, namely a Sensory Substitution process. Sensory Substitution (SS) is mostly the only way to

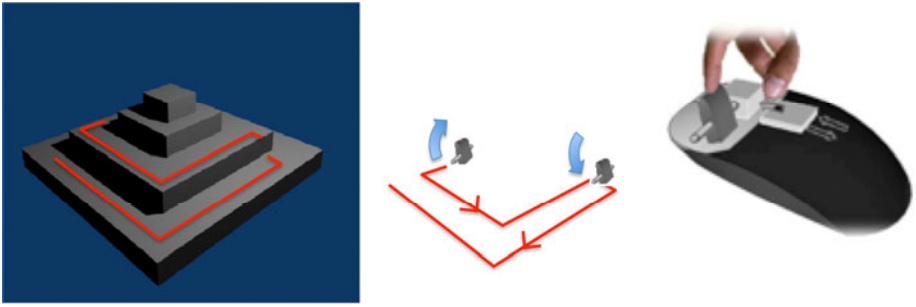


Fig. 1. The taxel-based device (right side) and the way tactile feedback is provided during the exploration (center) of a virtual object (left side)

display feedbacks and descriptions of a remote world in mediated interactions. Substitution occurs when information, which is normally dedicated to the sensory modality X, is displayed and successfully integrated through sensory modality Y.

Sensory Substitution is needed when one needs to convey information about radiation, temperature, pressure, levels of gas concentration, etc. Usually, the visual channel is the best candidate for this task. However, we need to estimate the cognitive cost of such transfer, since, generally speaking, not every modality Y is suitable to substitute X. One way to do it is to indirectly estimate the fatigue through performances.

However, the evaluation of the effectiveness of such sensory transfer does not generally go beyond qualitative evaluation; psychophysics-based techniques offer a more quantitative way to measure subjectively users' performances on the basis of chosen tasks. Even though this helps, few techniques that go beyond users' subjective interpretation exist today. To overcome this methodological barrier, researches are today more and more active, possibly adopting a multidisciplinary approach, to handle the strong need of objective measurements.

A quantitative assessment is at the same time a way to prove that a SS process has reached the goal, but also the validation tool for off-line analysis and improvement of new technological devices [1] [2].

This paper proposes methods to objectively assess the degree of sensory transfer in a visuo-tactile SS task, using a special purpose device, measuring signals which are linked to the degree of integration of spatial information and, indirectly, to the cognitive load.

For this purpose, we consider parameters extracted from neurophysiological signal, namely an electro-encephalogram (EEG), as suitable candidates for such objective evaluation. In fact, the high time resolution of neurophysiological measures makes possible an on-line monitoring of the subject's general conditions and particularly of the sensory and cognitive state due to the ongoing task.

Our objective is threefold: first, to stimulate a tactile sensory feedback, possibly evolving in a learning process, which allows to explore a 3D virtual environment. Second, to find a metric related to how much such exploration has contributed to build a mental map. Third, to find a correlation between our objective measures and the more and more difficult virtual environments that we present to users.

We will show evidence that specific brain signals related to spatial exploration are measured when objects are being virtually touched. We will also show that these signals modulate differently depending on the kind and complexity of the virtual objects. The remainder of the paper is organized as follows: Section 2 summarizes the state of the art on tactile SS systems and on the use of EEG-based measures; Section 3 describes our methodology and the experimental setup; results are detailed and commented in Section 4. Finally, Section 5 contains discussion and Section 6 concludes the paper.

2 State of the Art

The earliest SS devices converted visual stimuli to tactile representations for the blind and visually impaired [3][4]. Tactile-Vision Sensory Substitution systems (TVSS) were the earliest to be developed [5], in order to translate visual to spatial and temporal patterns of cutaneous information for blind people [6]. Some of the earliest works in this area were the development of the Optacon, which converted printed letters to a spatially distributed vibrotactile representation on the fingertip (a matrix of pins), using a miniature handheld camera [7]. Although reading speeds were significantly slower than Braille, the Optacon allowed blind people to access any text or graphics without having to wait for it to be converted into Braille. Early pioneering work in TVSS was also performed by Paul Bach-y-rita [8] and colleagues in the late 1960s: tactile displays could potentially provide a discrete and portable means of accessing graphical information in an intuitive non-visual manner. Many advances have also been made due to the appropriation of tactile displays for tele-robotics [9] and virtual reality, to represent physical contact with a remote or simulated environment guaranteeing a stronger tele-presence. However, many of these have been limited to engineering prototypes. To the best of our knowledge, none of them conquered a significant market share.

According to us, this happened because too much attention was given to precisely acquiring the sensory modality X, while less effort was dedicated to verify how "well" the substitution process was successful through the modality Y.

Previous studies [1][12] about substitution of vision with tact showed activity in visual cortex during tactile perception in sighted participants as well as in those who have experienced visual deprivation of varying duration. Dynamic changes in neuroimaging and spectral EEG were reported while processing visually/haptically presented spatial information [17]. One of the applications which allows to investigate the quantitative use of neurophysiological parameters for SS is the navigation [24] in virtual environments. By construction, such environments can provide controlled stimuli and are thus suitable to test the link between a given geometrical representation of space, even very simple, and the way it is learnt by the sole tactile feedback. We have already shown that this is possible in [2], and we assessed the degree of complexity of navigation-related tasks such as discrimination, recognition and reconstruction of geometrically simple virtual objects. In this study, instead, we attempt to find a correlation between certain neurophysiological parameters and specific events of the learning process of a simple tactile-based navigation task. We seek to derive, from such correlation, inferences about how far the device and its interface have carried out Sensory Substitution.

3 Methodology and Experimental Setup

Our experimental setup is aimed at measuring brain activity while performing the exploration of a 3D virtual environment with a single taxel-based mouse-shaped device. Such device (Fig. 1) provides the third dimension (the height) of virtual objects, while the first two dimensions (length and width of such objects) are given by the device position on a flat surface [2]. In practice, the exploration through this device approximates what happens when one single finger is exploring the physical profile of an object, where the higher the finger is lifting, the higher the touched object is. A user is then put in the condition to integrate tactile feedback together with proprioceptive feedback and form a cognitive space map. The virtual objects the users are asked to interact with are depicted in Fig. 2: each environment is a stair-shaped object, resembling a ziggurat, and their complexity is determined by the number of steps to explore and learn.

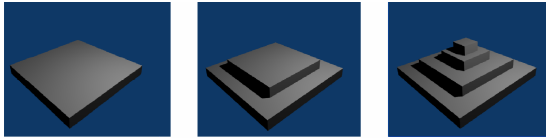


Fig. 2. The three virtual objects sensed through the device

Five subjects participated to the experiment, 3 males and 2 females, aged 29 ± 5 years old. All of them were right handed. The following protocol was applied:

- The subjects sustained a complete neurological/neuropsychological examination.
- The subjects' EEG signals were blindfolded and monitored in the following five phases:
 1. Pure resting state, followed by a visual stimulation (both with open and closed eyes).
 2. Pure motor task: subjects freely moved the device on a tablet, without getting tactile feedback.
 3. Exploration: subjects explored three more and more complex, virtual environments. Each environment was explored for 10 seconds and 10 times. A pure resting state of 10 seconds was induced between consecutive exploration trials. The switch between the exploration and the resting state was given by a start sound and a stop sound.
 4. Pure motor task
 5. Pure resting state.
- At the end of the whole experiment, subjects were unfolded and asked to depict and assign a difficulty's coefficient to each explored environment.

For what concerns signal acquiring and processing, monopolar EEG was recorded with Ag/AgCl cup electrodes at 14 active scalp sites according to the international

10/20 system. Electrooculogram (EOG), electrocardiogram (EKG) and electromyogram (EMG) were also acquired. Data were sampled at 1024 Hz. Also the experimental video and the coordinates perceived by the subject (x, y and height of the virtual objects) from the device were recorded to study possible behavioral- neurophysiological relations. Ocular, cardiac and muscular artifacts were removed using Independent Component Analysis (ICA).

Matlab and EEGLab [26] [27] were used for the elaboration. More specifically, EEG was filtered (0.5-50 Hz pass band) and post-processed using averaging and spectral/wavelet analysis to analyze the spatial/time evolution of the EEG usual bands and the other measures around the start/stop sound.

For each subject and each phase of the experiment (i.e. phases 2-4), we obtained from the raw EEG signal the independent components using ICA, which is widely used to reconstruct the localization (i.e. the spatial distribution) and the evolution (usually the time-frequency distribution) of the processes and sources generating the EEG signal.

We then sought a global result (mean topographical distribution and mean time frequency distribution of the clustered components from different subjects) for the whole studied group (as other works do [28]), regarding each single phase of the experiment. To achieve that, we computed desired condition-mean measures used to determine the cluster 'distance' of components from each other using a palette of standard EEGLab measures: event related potential, power spectrum, event related spectral perturbation, inter trial coherence, as well as the component scalp maps (interpolated to a standard scalp grid) and their equivalent dipole model locations.

Then, the components of the subjects were clustered using the K-means algorithm.

4 Results

The resting brain signals, according to literature, showed a wide presence of *alpha* (8-12 Hz) band with a particular concentration in the occipital region [28].

For both the pure motor and exploration phases, we studied the evolution of the power corresponding to some known EEG bands around the event given by the sound (which acts as the trigger, necessary for the analysis by means of averaging). For the two motor sessions, Fig. 3 shows the topographical distribution (left panel) of each single component contributing to the cluster (smaller heads), and the mean spatial distribution of the cluster (bigger head), as well as their time-frequency (right panel) distributions. The deactivation, or Event-Related Desynchronization (ERD) of the *alpha* and the *beta* (16-32Hz) band after the start sound (in blue) are an expected result: in fact, they are linked to the introduction of an external-related task, which is actually the movement of the arm of the user following the start sound. This complies with previous literature [29].

Fig. 4, instead, shows the same signal analysis applied to the exploration and tactile discovery of the 1-step ziggurat. In the frontal cluster, an evident Event-Related Synchronization (ERS) of the *theta* (4-8 Hz) band (in red and yellow) can be seen: in literature [17], this fact has been related to spatial processing and memory activation used to build a mental imagine of real or virtual objects.

In the case of the second exploration session of phase 3 (2 steps), as depicted in Fig. 5, two clusters were individuated. The most relevant is the frontal, which shows a ERS not only in the *theta*, but also in *sigma* (12-16Hz) bands and a ERD, in the *alpha* and *beta* bands: this can be related [22] to the augmented effort in discovering the internal details and it is a sign of cognitive effort.

Finally, the case of the most complex environment (4 steps), is represented in Fig. 6. The fronto-central location with an ERS in *theta* and *sigma*, but this time also in the *gamma* (32-50 Hz) bands and an ERD similar to the 1-step and 2-steps cases.

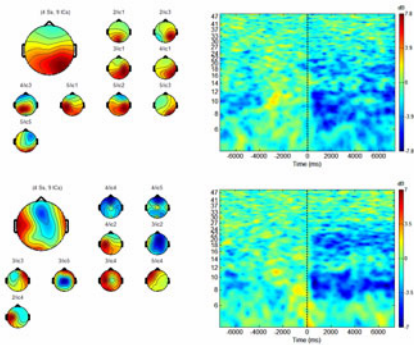


Fig. 3. Pure motor session. Topographical and time-frequency distributions of clustered components. Two clusters are found, both showing a general EEG deactivation, especially in the *alpha* and *beta* bands after the starting sound ($t \geq 0$).

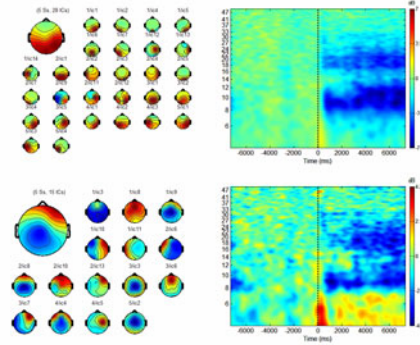


Fig. 4. One step exploration session. Two clusters are found. One mainly frontal shows an ERS in the *theta* EEG band and a ERD in the *alpha* and *beta* bands for $t \geq 0$.

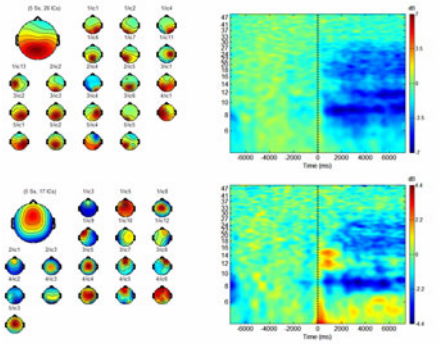


Fig. 5. Two steps exploration session. The frontal cluster shows a ERS not only in the *theta*, but also in *sigma* bands and a ERD in the *alpha* and *beta* bands, similar to the 1-step case.

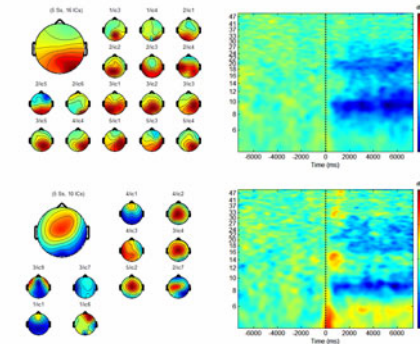


Fig. 6. Four steps exploration session. The fronto-central cluster shows a ERS in the *theta*, *sigma* this time also in the *gamma* bands and an ERD similar to the 1-step and 2-steps cases.

Table 1. Summary of EEG-based measures, for increasing complexity of the virtual environment. ERS_{FC} is the event related synchronization at the fronto-central location. Clearly the progressive synchronization of theta, sigma and gamma bands is related the progressive increased complexity.

$t>0$	Motor	1 Step	2 Steps	4 Steps
[32-50 Hz]	-	-	-	ERS_{FC}
[16-32 Hz]	ERD	ERD	ERD	ERD
[12-16 Hz]	-	-	ERS_{FC}	ERS_{FC}
[8-12 Hz]	ERD	ERD	ERD	ERD
[4-8 Hz]	-	ERS_{FC}	ERS_{FC}	ERS_{FC}

The *gamma* band is related to cognitive efforts. Interestingly, the *gamma* activation was absent in the unique subject who was able to perfectly recognize the four-steps zigurat, while in other subjects the same activation even *preceded* the starting sound.

We summarize the detected variations in the EEG bands, just after the starting sound, in Table 1: clearly, as the virtual object is more complex, more EEG bands and more high frequency signals are activated, all by increasing the effort needed to reconstruct the virtual object.

These neurophysiological variations seem to have a certain relationship with the type of strategy of exploration as will discuss in the next section.

5 Discussion

The aim of our work is to identify possible brain reaction during the employment of a new technological device which can give a tactile representation of a virtual environment. We also acquired a baseline situation at rest and a pure motor task in which nothing else was requested than freely moving the device without spatial-related tactile stimulation. Such situation significantly differs from the signals recorded during the exploration of the three virtual objects, clearly showing that looking at EEG time-frequency components is consistent for tactile-based spatial reconstruction tasks.

The reconstructing of the 3D shape of the first object was successful for all the subjects. Thus, the slower EEG bands are well associated with the spatial processing.

The situation radically changed in the case of a two steps structure. All subjects understood they had explored a centered symmetrical object, and were able to delimitate its bounds. However, only two subjects correctly reconstructed the internal structure. Observed mistakes were an unconscious smoothing and interpolation of the steps giving an appearance of a continuous conic pyramid. Subjects also reported in this case a strong increase in difficulty. This copes with our findings, where faster EEG bands, related to the reconstruction efforts, are captured together with the slow ones, related to spatial processing. Finally, the most complex situation presented a dramatically greater difficulty as reported by four subjects. Only one was able to correctly identify all the structure.

Four subjects felt great surprise when, after the experiment, a small plastic model of the four steps *ziggurat* was shown. Correspondingly with this complexity and difficulty, the even faster EEG band (*gamma*) were found together with the *theta* and

sigma. Some important process are related to this band, in particular the brain programming and the cognitive load.

In some trials, in fact, we even found activations in this band *before* the starting sound, i.e. when the users was not moving any body part: we speculate that this can be related to a user mentally programming the future movements or re-working the acquired information.

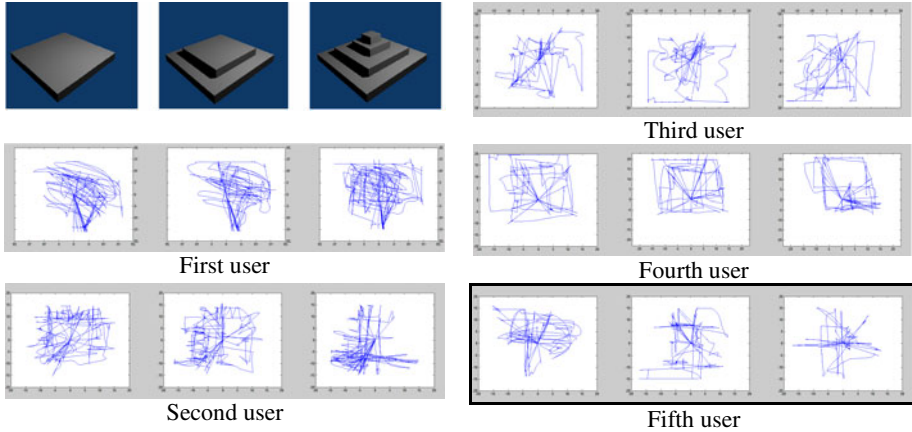


Fig. 7. Trajectories and strategies employed in the exploration of the three environments by five subject studied. Only the last subject was able to recognize the most complex environment, showing a different strategy and a clear easiness in the use of the device.

Fig. 7 shows the trajectories that the mouse virtually traced on the tablet: interestingly, the user with the best performance - the fifth - shows an exploration strategy more regular than the others. We emphasize that this user did not show a significant activation of the *gamma* band with any of the three objects, thus providing additional evidence to our hypothesis. In all cases, many of the occurred mistakes were probably ascribable to a non-uniform (e.g. insufficient in some areas) sampling of the explored space, as can be observed in Fig. 7: subjects generally over-explored a part of the environment probably making some kind of “inference” on the other parts. Another important source of misunderstanding can be the orientation angle of the mouse (which is integral with the hand and, to some extent, with the arm) with respect to the tablet, a fact which is common among PC users, but intuitively largely compensated by the visual feedback, which is absent here. In Fig. 7 the first and second user are have in fact exploration strategies with straight lines rotated CW, which implies to “observe” an object rotated CCW. It can also be seen that users generally develop two strategies: the first aimed at “circumnavigate” the objects, individuating the boundaries of the whole structure, the second, mainly radial, can be referred to the internal navigation of the objects aimed at reconstruction of the details. We emphasize that we cast the problem of visuo-tactile Sensory Substitution in its worst scenario, i.e. with minimal tactile information, almost no training at all and with a reconstruction task: this was done on purpose to collect the immediate mental reaction and effort of users and to avoid bias due to different learning curves.

6 Conclusions

In this paper we proposed a method to objectively assess the degree of sensory transfer in a visuo-tactile Sensory Substitution task. We showed that even with a single taxel-based device, users are able to discover and reconstruct some virtual objects of increasing geometrical complexity. We also showed that an objective measure of the information acquisition process through Sensory Substitution can be found: the spatial representation of the discovered objects, an increasing difficulty within the reconstruction task, as well as brain programming, are related to the relative activation/deactivation of specific EEG bands.

Such metrics are the first step towards a more objective assessment of the issues underlying tele-robotics tasks when sensory deprivation occurs.

Our metrics also provide an evaluation tool for the design of devices useful for the navigation of visually impaired people.

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Can I Help You?

A Spatial Attention System for a Receptionist Robot*

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Abstract. Social interaction between humans takes place in the spatial dimension on a daily basis. We occupy space for ourselves and respect the dynamics of spaces that are occupied by others. In human-robot interaction, the focus has been on other topics so far. Therefore, this work applies a spatial model to a humanoid robot and implements an attention system that is connected to it. The resulting behaviors have been verified in an on-line video study. The questionnaire revealed that these behaviors are applicable and result in a robot that has been perceived as more interested in the human and shows its attention and intentions to a higher degree.

1 Introduction

To let robots work and cooperate in domestic or public human environments, it is necessary for humans to interact with them without the need for special training or external instruction [1]. At the same time, the acceptance of a robot fundamentally depends on social factors in that people feel comfortable and confident during an interaction [2]. Therefore, a general goal in human-robot interaction (HRI) is to understand and mimic communicative cues observed in human-human interaction (HHI). Recent work in social robotics has explored these aspects in distant interactive situations (in terms of proxemics) as well as close-up situations (in terms of joint attention). In this paper we are looking at the intersection or transition between close and distant HRI, in particular, at the distance-based modification of attention behaviors while a person is approaching the robot. As also reported in [3], the initiation period is the most critical for a successful human-robot interaction. In most close-up experimental scenarios the human partner is externally briefed about the setup and task, while in most distant experimental setups the robot does not show any reactive or initiative behavior apart from approaching. Such studies typically stop just before the actual communication is established. Within this work, we provide a robot with

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a system that allows it to respond to proxemic features in an interactive situation. Particularly, the robot is able to use the distance to a human as an input that triggers a behavioral output that is based on proxemic cues. The resulting robot's attention is made transparent by the body posture, facing direction, and gaze so that, in turn, the human is aware of the intentions of the robot.

This becomes relevant in receptionist scenarios, for example. To deploy a robot into a hotel lobby or a museum, one should consider which impact a robot's presence could have on the human. E.g., people far away may be less interested in an interaction with the robot than people coming closer towards it. With the presented system, the robot is able to respect the dynamics that humans use by adapting its attention accordingly. An interaction can actively be established by signalling the human interest in an increasing manner as she comes closer towards the robot.

In the following, we conducted a video study to reveal whether the dynamic adaption of attention is accepted by the users and if it lets them understand better how the robot can be used.

1.1 Related Work

Social cues in HRI have been extensively explored in recent years. A first part is dedicated to proxemics as introduced by Hall [4], i.e. respecting people's personal spaces. Comparing to HHI, they report similar factors influencing proxemic behavior in HRI [5,6,7]. Kirby et al. [8] and Pacchierotti et al. [9] study this for person following or passing behaviors. Takayama et al. [5] even find for HRI settings that proxemics is influenced by eye contact which suggests a tight coupling of different communicative cues.

While studies on proxemics typically focus on distant human-robot interaction, another line of work looks at maintaining user engagement in close human-robot scenarios [13,10]. Here one of the key ideas is to convey intentionality either by appropriate feedback or mixed-initiative strategies that guide the partner through the interaction. An interesting result by Muhl & Nagai [11] suggests that – once a mutual interaction between the partners has been established – short distractions of the robot leads to a higher engagement of the human partner.

2 Scenario

Our receptionist scenario consists of a multi-modal interaction system that is implemented on a humanoid robot. It is designed to help users find their ways to offices of colleagues or other university buildings. For the interaction with a human it can use gesture and speech. While the basic interaction with the robot has already been shown in [12], we now present nonverbal means for establishing interaction spaces *before* and maintain them *during* the actual interaction at the desk.

Therefore, we have enhanced our robot with an attention system and a method to calculate the distance to a person in the same room.

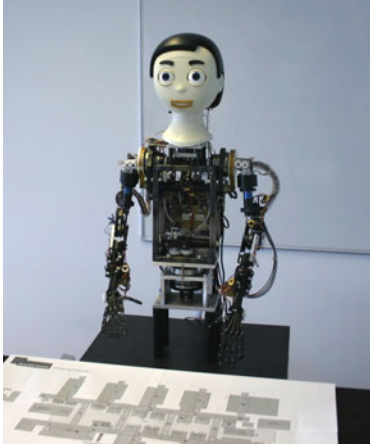


Fig. 1. Picture of the hardware setup. The robot torso BARTHOC with the Flobi head has been placed behind a desk to act as a receptionist.

2.1 The Robot System

The proposed system is implemented on the immobile humanoid robot BARTHOC [13]. Due to huge improvements in the technical construction and design, the original head has been replaced by a newer version called Flobi [14]. It has been explicitly designed to produce social behaviors and human-like feedback [15] as well as integrating sensor functionality.

Of the 45 degrees of freedom (DOF), only the hip, head, and eyes are being used in this scenario (6 DoF). The head is equipped with two fire-wire cameras in the eyes and microphones in the ears. Since the cameras are attached to the eye-balls, their image always reflects the current view direction of the robot. For an image of the hardware setup please see Fig. 1.

2.2 The Proximity-Based Person Attention System

The person attention system is based on a simple sensor-actor loop that follows the face of a human using of the in-eye cameras of the robotic head. First the distance and deviation of the human face from the camera center is computed. Then the compensation pan-tilt angles are decomposed differently between the hip, head_turn, and eye_turn of the robot depending on the intimate, personal, social, or public distance class.

Face localization is done with a standard face detection algorithm [16] providing a 2D rectangle at image coordinates. Then, the distance is calculated assuming an average size of the detected rectangle on a real face (height $\approx 15cm$). It is estimated considering the horizontal camera resolution and the opening angle of the camera. The distance of a person is defined as the mean of the horizontally and vertically estimated face distance. According to Hall [4], we can now classify whether the person stands either in an intimate, personal, social, or public distance to the robot. In Fig. 2 you can see a human in a close social distance to the robot, ready to enter the personal distance.

Compensation Angles are computed for the horizontal pan and vertical tilt in order to keep the face in the image center which reflects the current gaze direction of the robot. Because the angle compensation (ϕ_{pan}) for the 2D deviation

(d_x) in the image is distant specific, this already leads to a stronger engagement of the robot when the person comes nearer. For the intimate distance a factor of $s = 2^\circ$ is used, $s = 1.5^\circ$ for personal, $s = 1^\circ$ for social, and $s = 0.5^\circ$ for public distance (with $\phi_{pan} = -sd_x$). If the compensation angle is below a threshold no movement is performed.

Decomposition of Compensation Angles Into Robot Postures is done specific for the distance class.

These relative turn and pitch angles are transformed to robot postures by the motor control component. The turn is distributed among the hip, head_turn, and eye_turn joints. The head_pitch and eye_pitch joints combine to the overall pitch angle.

Here, a second method for adapting the attention of the robot to the current interaction situation is applied. Depending on Halls distance classes [4], the usage of certain joints is restricted. A so-called inertia value determines to what extend the complete range of a joint is being exhausted. A virtual boundary limits the theoretically possible angle that a joint can be maximally moved.

With a high inertia value the individual joints are limited least, i.e. they can be moved to half of their real maximum. Because of that, most of the movement is accomplished using the eyes only. The head is used for changes in gaze directions that cannot be reached by the eyes alone. The hip remains practically unused. When the inertia is set to medium, the joints are virtually limited to use only 40% of their range. In this setup, the head is used much more frequently for changing the posture. A low inertia value limits the joints to 30%. Therefore, also the hip joint contributes very often to the actual turn value.

The limitation above does not introduce a hard boundary, but a soft one instead. If the angle cannot be distributed the aforementioned way, then the remaining part will be added to joints that have not already reached their real maximum.

Attention Distractors. Since humans do not stare consistently at each other during a conversation [17], we also suggest the implementation of distracting random gazes. These shift the robots focus from a human to another location for a short time of approximately one second. The robot's attention seemingly gets caught by some other entity in the room.

The resulting view angle is decomposed exactly the same as in the case of a detected face. The only difference is in the usage of joints. The inertia value is even higher than if a human is detected. Thus, the joints are only limited to 70%

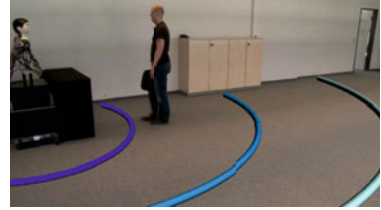


Fig. 2. A person in social distance to the receptionist. The augmented circuits surrounding the robot mark the different distance classes from proxemics theory: dark blue surrounds the personal, lighter blue marks the social, and the outer circle limits the close public distance.

of their range. This way, one can assure that the robot does not turn its body away from a human in a face-to-face situation.

3 Experimental Setup

The proposed attention system has been evaluated with the help of an on-line questionnaire. Participants had to answer questions referring to videos that show an interaction situation. Two main questions have been addressed in this survey:

1. To what extent does the dynamic modification of the attention behavior alter people's perception of the robot?
2. Which influence does the addition of random gazes have on the perception of the robot?

Videos of the Different Conditions. We videotaped an interaction between a human and our robot. This way, we could ensure that each participant group rates exactly the same robot behaviors. Furthermore, the experimental results could not be influenced by the various ways people would try to interact with the robot.

The robot has been placed behind a desk in the corner of a room: A human enters this room, walks through it, and eventually stands in front of the desk. When the human arrives and enters the robot's personal distance, it says: "Hello, my name is Flobi. How may I serve you?". The human answers: "Tell me the way to Patrick's office".

The nonverbal behavior of the robot differed between trials and was categorized into eight different conditions:

- Z.** The robot does not move at all (**Z**ero movement).
- R.** The robot's gaze is shifted only **R**andomly.
- CN.** The robot tries to focus its counterpart but acts as if he were permanently in a personal (**C**lose) distance, **N**o random movements added.
- DN.** Again, the human is focused. This time, the movement is **D**istance dependent.
- FN.** The gaze is shifted as if the person were in a public (**F**ar) distance.
- CR.** Same as CN, but **R**andom movements are added in between.
- DR.** Distance dependent as DN, but with **R**andom movements.
- FR.** Like FN, with **R**andom movements added.

The interaction has been recorded from two perspectives. One camera has been following the human all the time and another one shot a close-up of the robot. Both of the videos have been combined to a single one that shows the perspectives side by side. In Fig. 3 you can see three screen shots of the resulting video that has been shown to the participants.

All of the videos have been synchronized to the frame one could spot the robot in the left video for the first time. They fade to black while the human answers the robot to suggest an ongoing interaction between the two agents.



Fig. 3. Video screenshots from the study. The left camera image follows the person as he comes closer to the robot. In the right image a close-up of the robot is shown to let people identify the robot's motions reliably.

Questionnaire Design. The participants had to fill out an on-line questionnaire where they were shown three videos. The first video always showed the Z condition, in the second and third video, the participants could see two videos from different conditions. To prevent side effects of sequence, these videos were shown in random order. Altogether participants can be categorized into the following five groups:

- NR.** Differs in containing **R**andom movements or **N**ot.(DN and DR, or FN and FR, or CN and CR)
- FD.** The robot acts as if the human is either **F**ar away or dynamically adjusts its movement to the **D**istance.(FN and DN, or FR and DR)
- CD.** The robot treats the human either as **C**lose to the robot or dynamically adjusts to the **D**istance.(CN and DN, or CR and DR)
- CF.** The robot acts as if the human is either **C**lose or **F**ar away.(CN and FN, or CR and FR)
- RR.** The robot only shows **R**andom movements in both videos.(Control group)

Participants were presented each video. They had the possibility to watch the video as a whole and as many times as they wanted. Beneath the video, the participants were asked to rate certain aspects of the robot's behavior on a five-point Likert scale (0-4):

- The robot's *Interest* in the human
- The *Appropriateness* of the robot's behaviors
- The robot's *Human-Likeness*
- The *Naturalness* of the robot's movements
- How much *Attention* the robot payed to the human.
- The robot's *Autonomy*
- How much of its *Intention* the robot revealed.

Participants. Altogether 111 users participated in the study, of which 39.6% were female and 60.4% were male. Their age varied between 16 and 70 years with an average of 30.5. Almost half of them were affiliated with the university, either as students (31.8%) or as scientific staff (18.2%). The vast majority of 88.3% were native German speakers. The rest stated a high understanding of English or the German language. The questionnaire was available in English and German languages, so the questions could be well understood and answered by every participant.

The robot experience varied greatly between subjects. A very large part (84.7%) did not rate their robot experience higher than average on a five-point Likert scale (0-4). The mean value for the participant's robot experience has been at 1.04. In contrast, most of them rated their computer experience either 3 or 4 (67.9%). With an average of 2.94, the computer knowledge seems to be fairly high among the participants. In general, one can say that although the majority of participants are naive to the subject, they have a common technical understanding.

4 Results

Answers to the questionnaire have been evaluated for significant deviations of their mean value. As a method for the comparison, a paired-samples T-Test with a significance level $\alpha = 5\%$ has been used.

4.1 Goal Directed Movements

Almost all of the questions asked produced significant differences between the Z video (zero movement) and every other video that was shown to the participants. Participants rated all of the robots attributes higher for videos that showed a moving robot than for a non moving robot ($\alpha = 5\%$, $p < .027$).

The RR group with 12 participants is an exception to the others: Videos that showed pure random movements only produced significant changes in the participants ratings for the robot's *Human-Likeness* and *Attention*. Instead, *Interest*, *Appropriateness*, *Naturalness*, *Autonomy*, and *Intention* could not be distinguished from videos without any robot movement. Table 1 shows detailed results of the RR group.

4.2 Distance Dependent Modification of Behaviors

Only one of the FD, CD, and FC groups showed significant deviations in the ratings of the robot's behaviors. Groups CD (21 users) and FC (24) did not show any differences between the two videos that were presented to them. Responses in the

Table 1. Mean ratings \varnothing from the RR group with 12 participants, sorted by the video type. The two-tailed significance $pR1$ of the differences between Z and R1 as well as $pR2$ between Z and R2 are also depicted if $p < \alpha$.

	$\varnothing Z$	$\varnothing R1$	$\varnothing R2$	$pR1$	$pR2$
Human-L.	1.00	2.00	1.82	.010	.025
Attention	.92	2.25	2.17	.001	.004
Interest	1.25	1.58	1.92	-	-
Intention	.92	1.33	1.42	-	-
Appropri.	1.67	1.75	2.00	-	-
Natural.	1.09	1.50	1.50	-	-
Autonomy	1.25	1.42	1.58	-	-

Table 2. Mean ratings \emptyset from the FD and NR groups, sorted by the type of video. The two-tailed significance p of the differences is depicted in the last column if it is below α .

	\emptyset F	\emptyset D	p		\emptyset N	\emptyset R	p
Interest	2.58	2.92	.036	Interest	2.30	3.22	.001
Attention	2.58	3.04	.043	Attention	2.42	3.23	.002
Intention	2.12	2.60	.020	Intention	2.15	2.74	.008
Human-L.	1.88	2.12	-	Human-L.	1.85	2.37	.037
Apppr.	2.50	2.58	-	Apppr.	2.26	2.33	-
Natural.	1.50	1.73	-	Natural.	1.59	1.78	-
Autonomy	2.00	2.23	-	Autonomy	2.19	2.33	-

(a) FD-group (26 participants)

(b) NR-group (27 participants)

FD condition (26) instead could be distinguished. Participants rated the robot's *Interest*, *Attention*, and its *Intention* higher in the distance dependent video than in the far away condition. The result of this comparison is shown in Table 2(a).

4.3 The Influence of Random Movements

The participants' answers of the NR group (27) differed significantly in four categories. The robot's *Interest*, *Human-Likeness*, *Attention*, and *Intention* have been rated better in videos with random movements (CR, DR, FR) than in videos without random movements (CN, DN, FN). Other attributes did not show significant differences in the users' ratings. See Table 2(b) for more detailed results.

5 Interpretation

The above results show that the presented system can serve as an entry point for a human-robot interaction. Each of the presented movement types is more appealing to a human user than no movement at all. Even totally random movements (RR group) suggest a certain human-likeness of the robot. The significance in the ratings of the attention in the random-only case might be caused by the fact that the robot accidentally looked straight into the human's eye as it began to speak. If this had not been the case, the attention ratings of the random behavior would possibly also not be distinguishable from the no-movement case.

Random gazes in conjunction with person-directed gaze can lead to a better user experience than person-directed gaze alone (NR group). Participants believed that the robot had more interest in the human, was more human-like, paid more attention to the human, and expressed its intentions to a greater degree when the robot exhibited random gazes.

At a first glance it might be confusing that especially the attention is rated higher when the robot looks away from time to time. We believe that these distracting looks actually help to communicate an attention to the human because

the robot re-focuses on the human every time it had looked away. Therefore, the robot shows that its attention is caught again by the human. While the random gazes help to assign a certain personality to the robot, they do not have an influence on the appropriateness, naturalness, of the behaviors and the autonomy of the robot. The robot apparently does not lose any of its functionality by the addition of distracting gazes.

No differences could be found between the groups that saw the two distance independent behaviors of the robot (FC group). The difference in these conditions obviously did not lead to a higher valuation in one of them. While all cases in this group differed significantly from the zero movement video, participants did not prefer one solution over the other.

Also the distance-dependent condition is not distinguishable from the condition in which the robot acts as if the person stands directly in front of it (CD group). We believe that this could be caused by the similarity of the videos for these cases. Participants could not really tell the difference between the two conditions. That might be a problem of the video itself but could also be a consequence of the experimental setup. Since people were not in the same room with the robot but saw a video instead, their comfortable feeling could not be violated by a robot that doesn't respect personal distances. Therefore, the ratings for the robot are almost identical in the case of direct response as in the dynamic case.

Between the far-away and the distance-dependent condition, significant differences could be found in the user's ratings of the robot's interest, attention and intention. Apparently, the robot was experienced as more responsive and expressive in general, if it uses more of its capabilities and turns its body earlier and more frequently to the interaction partner. Therefore, the distance-dependent behaviors should be preferred over the artificially restricted ones.

6 Conclusion

In this work, we have presented a robot equipped with a spatial model of its surrounding. Also, an attention system has been developed that controls the robot's movements. Both of these components have been combined in an integrated system that allows the robot to exhibit distance dependent social behaviors. We have shown that this system can serve as an entry point for a face-to-face interaction in a receptionist scenario and should be preferred over a non-moving or randomly moving robot.

While random movements alone are not suitable as an entry for the interaction, the overall behavior can benefit from the addition of random directions to the person-directed gaze. Involvement of the robot should be shown in a distance dependent manner. Restricting the robot's hip movement in face-to-face situations leads to a lower overall rating of the robot's responsiveness. The opposite case of immediate response remains a question that should probably be addressed again, since we have not found any significant differences but doubt that an immediate response would be appropriate under real-world conditions.

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A Persuasive Robotic Agent to Save Energy: The Influence of Social Feedback, Feedback Valence and Task Similarity on Energy Conservation Behavior

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Abstract. In this paper we explore the persuasive effects of social feedback provided by a robotic agent, on behavioral change. In lab experiments, participants had the opportunity to conserve energy while carrying out washing tasks with a simulated washing machine. Three experiments tested the effect of positive and negative social feedback and compared these effects to more widely used factual feedback. Results of these studies indicate that social feedback has stronger persuasive effects than factual feedback (Experiment 1) and factual-evaluative feedback (Experiment 2). In addition, an effect of feedback valence was found, demonstrating more conservation actions following negative feedback (social or factual) as compared to positive feedback. Interestingly, especially negative social feedback had the strongest persuasive effects (Experiment 1, 2, & 3), and task similarity enhanced the effects of negative feedback (Experiment 3). These findings have several implications for theory and design of persuasive robotic agents.

Keywords: Human-Robot Interaction, Persuasion, Social Feedback, Energy Conservation Behavior.

1 Introduction

The threats of growing CO₂-emissions and climate change effects necessitate technological solutions like more efficient devices. But consumer behavior also plays a crucial role in bringing down the level of energy consumption, which makes highly relevant which instruments can promote energy conservation behavior.

Recent reviews [e.g. 1, 9] indicate that, in general, mass media public campaigns seem to lack precision in targeting and message concreteness. In contrast, raising people's awareness of energy consumption by providing tailored feedback about their energy consumption (for example in kWh) can promote the achievement of behavioral change. However, weak linkages between specific actions and energy outcomes caused by low feedback frequencies (e.g. once month) and insufficient specificity of the feedback (e.g. household in general vs. specific person or specific devices) diminish their effectiveness. Persuasive Technology [see 6] that can intervene in user-system interaction might overcome these issues. That is, research by McCalley and

Midden [7, 8] suggests that Persuasive Technology that provides *interactive forms of feedback* can be effective in enhancing energy efficiency. By adding an energy meter (that gave factual feedback in kWh consumed as a function of programming choices made by the user, like water temperature, spinning speed or the duration of the washing cycle) to the user interface of a washing machine they achieved 18% of energy conservation both in lab and field studies.

In the present study we follow up on this work by aiming to increase the persuasiveness of technology through the introduction of Persuasive Technology that can provide social feedback—a social agent in the form of a social robot. Social reinforcement has been applied widely in many domains such as child education, therapeutic programs, health behavior and social interaction as a mechanism for behavioral change [2]. Social praise and compliments operate as positive incentives. Negative social incentives, like signs of disapproval, have been applied less widely, but nonetheless have been demonstrated to be effective as well [e.g. 13].

Social reinforcements delivered by human actors can be very effective, but would social reinforcement work as well when delivered by technology, that is, by a social robot? Media equation research [10] suggests that people show similar social behavior in interaction with computer systems as with humans. Social praise from a computer can enhance computer attractiveness, and make people feel better and more positive about interaction with a computer [6]. Despite the relevance of these findings, no direct evidence is available for effects of social reinforcements on behavioral change.

In the present research we want to explore the effectiveness of social feedback as provided by a smart robotic agent and compare this with the more widely used factual feedback, in particular its most effective form, *interactive* factual feedback [9].

The media equation studies suggest that people react similarly when confronted with computer or human agents. Social cues seem to automatically activate social reactions [6]. Therefore, we wanted to explore whether these conclusions would also hold for behavior change interventions through social feedback. It seems plausible that an intelligent system that is perceived as social actor can likewise influence the behavior of a person who receives social feedback from the system.

Surprisingly, social feedback by smart computer agents has mainly focused on positive social feedback only. We argue that the effects of negative and positive social feedback differ. Although negative feedback may be less pleasant for the user, there are reasons to expect significant outcomes from negative feedback. In general, negative events show, almost universally, higher impacts than positive events and bad information is usually processed more intensely than positive information [4, 11, 12]. Basic explanations for this can be that, in an evolutionary sense, negative information is more valuable for adaptation than positive information. Ignoring danger is in general more threatening for survival than missing a positive opportunity. Negative information signals a need for change, thereby feeding the self-regulatory system needed for adapting to changing circumstances [3]. Negative information has a higher level of diagnosticity: One accident indicates system unsafety, while only long periods of flawless functioning deliver a feeling of safety. Following this reasoning, we expected negative feedback to be more effective than positive feedback.

Considering the social nature of the feedback, it seems not very plausible that people will be impressed by social reactions that cannot be linked to an agent, that is, an actor that is capable of making an independent value judgment. While human beings

may differ in the level of agency attributed to them, this is probably truer for robotic agents. To explore this expectation we included in our study a manipulation of perceived agency expecting that social feedback provided by an agent with high perceived agency would be more persuasive than an actor with low perceived agency.

2 Experiment 1

To study the influence of social feedback by a smart computer agent on user behavior we set up an experiment in which subjects received social feedback from a robotic agent while carrying out tasks in which they could conserve energy. More specifically, we tested the effects of social feedback compared to factual feedback, the effect of positive vs. negative feedback and finally we explored the effect of low vs. high perceived agency as a characteristic of the feedback source.

2.1 Methods

Participants and design. Thirty-three participants (27 men and 6 women) were randomly assigned to one of three experimental conditions: a factual feedback condition, a low-agency social feedback condition, and a high-agency social feedback condition. In addition, each participant completed 10 washing trials, which composed the 10 levels of our second independent variable. All participants were native Dutch speakers. The experiments lasted 30 minutes, for which participants were paid 3 Euros (approximately \$3.75 U.S. at the time this study was conducted).

Materials and procedure. Participants were invited to engage in an experiment using a simulated washing machine., and were seated individually in a small room. For participants in social feedback conditions, an iCat was positioned on the participants' desk, next a computer. An iCat is a robot developed by the Philips Corporation in the form of the stylized head of a cat that is able, among others, to display social expressions by moving lips, eyes, eyelashes, and eyebrows, and by playing speech files. For participants in the factual feedback condition the iCat was not present. For all participants, a simulated washing machine panel was presented in the top half of the screen (see Figure 1). Only for participants in the factual feedback condition, we added an energy meter to the panel. This energy meter clearly displayed the amount of electricity in kWh corresponding to the chosen washing program. For all participants, in the bottom half of the screen, a program displaying the instructions, tasks and questions was presented. This program started with general introductions, and then instructed participants about the task: they were asked to complete several simulated washing trials on a computer. Next, participants were instructed on how to program the washing machine. Participants then were instructed to do each washing as good as possible, that is, to clean the clothes and not damage them (e.g., by washing a woolen sweater at 90°C, causing it to shrink), but also to use as little electricity as possible. So, participants were given two (partly contrasting) goals. To save energy, other settings are optimal (e.g., washing cold) than to clean clothes. Thereby, we motivated participants to use (some) energy, while installing also the motive to save energy for which we could then provide feedback.

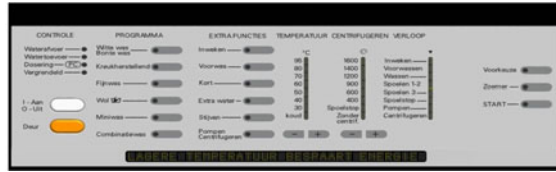


Fig. 1. The iCat and corresponding washing machine interface

To participants in the factual feedback condition the program next explained the energy meter. To participants in the low-agency social feedback conditions, the program told that this washing machine was equipped with an "advanced electronic device" (the iCat) that allows it to give feedback on electricity consumption. These instructions underlined that the washing machine was the director of all expressions presented on the "device". Next, participants were instructed on how this device would be giving them feedback. To participants in the high-agency social feedback condition, the program described the iCat, named "Victor" and its characteristics. They were told that Victor was a very advanced robot that had a little mind of its own, and would be informing them about energy consumption. After one practice trial, the actual 10 washing trials started. For each trial (and also the practice trial), participants were instructed to complete a specific type of wash (e.g., "wash four very dirty jeans"). Each description of a specific type of wash was randomly drawn from a collection of thirty descriptions of common washes, for each trial of each participant such that each participant completed ten different washes. During each washing trial, participants were able to change settings on the washing machine panel until they were satisfied and then pressed a "start" button. Participants received feedback about the energy consumption of the chosen washing program after each change of settings. Participants in the factual feedback condition received factual feedback through the energy meter. Likewise, participants in both social feedback conditions received social feedback through the iCat during each trial. For small deviations from the middle of the scale, the iCat showed one of three different positive respectively one of three negative facial expressions (feedback level 'low', e.g., a smiling face or a sad face), for more grave deviations, the iCat illuminated little lights at the top of its ears (feedback level 'medium', green for positive feedback and red for negative feedback), and for the most grave deviations the iCat uttered a positive or negative word (feedback level 'high', e.g., "Fantastic!" or "Gruesome!"). Furthermore, in the *low*-agency social feedback condition the iCat used only one specific brief speech utterance (drawn randomly from a set of six) repeatedly to give positive social feedback during the washing trials, and another to give negative social feedback (drawn from a set of six). In contrast, the iCat in the *high*-agency social feedback condition used various synonyms: one of six different speech utterances (drawn from the same set of six positive utterances) to give positive social feedback, and one of six others for negative social feedback (drawn from the same set of negative utterances).

After all 10 washing trials had been completed, participants answered several demographic questions, were debriefed and thanked for their participation.

2.2 Results

For each of the ten washing trials of each participant, we calculated the difference between the amount of electricity a participant's settings would have used, and the average usage of electricity for that specific type of wash (e.g., the 4 very dirty jeans) by all participants in our study. We labeled this the energy consumption score. This way, we were able to calculate a dependent variable that indicated the difference between a reference amount of electricity needed for a specific type of washing task (at least in the current study) and the electricity a participant chose to use.

This energy consumption score was submitted to a 3 (feedback condition: factual feedback vs. low-agency social feedback vs. high-agency social feedback) \times 10 (washing trials: 1 to 10) MANOVA, with the last variable within-subjects. Our expectations were confirmed. That is, we found that participants who received social feedback consumed less electricity than participants who received factual feedback, indicated by a main effect of feedback condition, $F(2, 30) = 3.42, p < .05$. More specifically, participants who received low-agency social feedback ($M = -.02, SD = .16$) and participants who received high-agency social feedback ($M = -.05, SD = .17$) used less electricity than participants who received factual feedback ($M = .11, SD = .11$), $F(1, 30) = 6.64, p < .05$. Note that these are energy consumption scores—therefore this indicates that factual feedback leads to more electricity consumption than the average usage for a specific type of wash,

Importantly, the electricity consumption of participants who received low-agency showed no difference from the electricity consumption of participants who received high-agency social feedback, $F < 1$. Furthermore, we found no effect on electricity consumption by washing trial condition, nor an interaction, both F 's < 1 .

To be able to distinguish the effects of positive and negative feedback we calculated an index based on total number of actions of users in the user interface. This means that we not only included the final choices per trial, but all the preceding programming choices. As explained in the method section, these were all followed by (factual or social) feedback, either positive or negative. The index subtracted for each action the following choice, in terms of energy consumption effect, from the current choice, thereby indicating whether the feedback resulted in a higher or lower energy consumption score for the next following choice.

These scores were submitted to a 3 (feedback condition: factual feedback vs. low-agency social feedback vs. high-agency social feedback) \times 2 (type of feedback: positive vs. negative) \times 3 (feedback level: low vs. medium vs. high) MANOVA. A main effect was found of type of feedback, indicating a stronger conservation effect of negative feedback ($M = -.21, SD = .40$) compared to positive feedback ($M = .10, SD = .39$), $F(1, 786) = 164.51, p < .001$. A second main effect was found of feedback level, $F(2, 786) = 10.13, p < .001$, indicating the strongest effect on behavior at the high feedback level ($M = -.29, SD = .59$) and weaker effects at the low ($M = -.02, SD = .34$) and medium ($M = -.02, SD = .31$) levels. Furthermore we found two significant 2-way interactions: condition \times type of feedback ($F(2, 786) = 4.60, p = 0.01$); feedback level \times type of feedback ($F(2, 786) = 47.04, p < 0.0001$) and a significant 3-way interaction (condition \times type of feedback \times feedback level; $F(4, 786) = 4.15, p = 0.002$). More specifically, these findings showed that the greatest changes to conservation behavior were achieved after negative feedback (compared to positive

feedback), in particular at the highest feedback level (including speech). As expected this effect was strongest for the participants who received social feedback. Surprisingly this effect was stronger in the social feedback condition with low agency compared to the social feedback condition with high agency.

In sum, our findings of study 1 suggest that social feedback has a higher impact on behavior than factual feedback. Furthermore, we found that verbal reactions of the robot drive social feedback effects. Facial expressions and light signal only did not generate effects. Also, negative feedback (compared to positive feedback) had the strongest effect on conservation behavior, especially negative feedback given by the iCat. Finally we did not find an effect of our perceived agency manipulation.

Before drawing firm conclusions, however, we performed a second experiment to replicate these results. In addition, in the second experiment we manipulated feedback type (positive versus negative) between participants. That is, in Study 1 all participants received both positive and negative feedback. Thereby, any effects of negative versus positive feedback might be dependent on the presence of the opposite type of feedback, and therefore we cannot draw the strong conclusion that indeed solely negative feedback leads to the lowest energy consumption.

Furthermore, in Study 1 factual feedback was fundamentally factual in that it consisted of the amount of energy used presented on energy bar (as described in the Method section of Study 1). However, thereby the factual feedback was not only non-social, but also non-evaluative. That is, whereas in the social feedback of Study 1 an evaluation was included (as e.g. in “Fantastic!”), an explicit evaluation was not included in giving factual feedback by setting the energy bar to for example 1,14 kWh. Because with our manipulation of feedback condition (factual feedback vs. social feedback) we mainly wanted to influence whether feedback was social in nature or not, we changed the content of the factual feedback in Study 2 to include an evaluation. We did this by introducing a separate feedback device (labeled the “energy lamp”) to give factual-evaluative feedback. This energy lamp changed colors and produced a sound depending on the energy used in a washing trial (as a function of programming choices made by the user). For example, to give feedback indicating high energy consumption, the energy lamp would change color stepwise from white to dark red and back, and an unpleasant buzzer would sound. If the participant made an energy-efficient choice the lamp would stepwise change color from white to dark green and back and the sound was more pleasant. This setup made the evaluative resolution in the condition comparable to the social feedback condition. In a pretest the evaluative meanings of lamp and buzzer signals were tested and confirmed.

3 Experiment 2

Study 2 was completely identical to study 1, except for the following changes. First, we manipulated positive versus negative feedback between participants instead of within participants (Study 1). Second, the energy bar used in Study 1 was not shown in the factual-evaluative feedback conditions. Instead, next to the washing machine simulation display, a CRT monitor and two loudspeakers were positioned. When no feedback was being given, the screen was white and the speakers silent. Screen and speakers were used to give participants factual-evaluative feedback by changing the

color of the screen combined with a sound. In negative feedback conditions, factual evaluative feedback was given when participants used more energy than the middle of the scale. This was done by gradually changing the color of the screen from white to red and back within 3 seconds. In addition, an unpleasant sound (a buzzer) was played through the speakers for one second. The strength of the red color and the loudness of the sound depended on the amount of energy consumed by a participant's settings. If e.g. a setting used much energy, the screen changed color to dark red, and a loud buzzer sounded. In positive feedback conditions, factual evaluative feedback was given in an identical fashion, but now the screen color changed from white to green, and the sound played was a pleasant ring. Level of detail of the factual-evaluative feedback was similar to that in social feedback conditions.

3.1 Methods

Participants and design. Sixty-five participants (47 men and 18 women) were randomly assigned to one of four experimental conditions: 2 (feedback condition: factual-evaluative feedback vs. social-evaluative feedback) x 2 (feedback type: positive vs. negative). In addition, each participant completed 16 washing trials, which composed the 16 levels of our third independent variable.

3.2 Results

The energy consumption score was submitted to a 2 (feedback condition: factual feedback vs. social feedback) x 2 (feedback type: positive vs. negative) x 16 (washing trials: 1 to 16) MANOVA, with the last variable within-subjects. As expected, first, we found that participants who received social feedback consumed less electricity ($M = -.04$, $SD = .26$) than participants who received factual feedback ($M = .03$, $SD = .27$), indicated by a main effect of feedback condition, $F(1, 976) = 19.78$, $p < .0001$. Second, we found the expected main effect of type of feedback, indicating a stronger conservation effect of negative feedback ($M = -.03$, $SD = .26$) compared to positive feedback ($M = .03$, $SD = .27$), $F(1, 976) = 12.12$, $p < .01$.

Third, we found the expected interaction of Feedback Condition x Feedback Type, $F(1, 976) = 12.12$, $p < .01$. Further analyses indicated that participants who had received positive feedback and who received social feedback consumed as much electricity ($M = .01$, $SD = .25$) as participants who received factual feedback ($M = .04$, $SD = .29$), $F(1, 1037) = 1.77$, $p > .18$. However, of the participants who had received negative feedback, those who received social feedback consumed less electricity ($M = -.08$, $SD = .26$) than those who received factual feedback ($M = .03$, $SD = .25$), indicated by a simple main effect of feedback type, $F(1, 1037) = 21.07$, $p < .0001$. Furthermore, of the participants who had received social feedback, those who received negative feedback consumed less electricity than those who received positive feedback, indicated by a simple main effect of feedback condition, $F(1, 1037) = 15.47$, $p < .0001$, whereas participants in the group of participants who had received factual-evaluative feedback and who received negative feedback consumed as much electricity as participants who received positive feedback, $F < 1$.

Next to replicating study 1 in showing strong persuasive effects of social feedback (provided by an embodied agent), study 2 also replicates study 1 in suggesting that providing single negative feedback is more effective than providing single positive

feedback. We argue that an important reason for the effectiveness of negative feedback is that negative feedback is especially effective in situations that allow people to avoid aversive consequences. Earlier research [see 14] suggests that people seek information about impending dangers only when they see a possibility to avoid negative consequences. Therefore, we argue that the effects of negative feedback are moderated by the amount of options to avoid negative consequences that tasks allow for. And especially when tasks that people have to perform are relatively similar (as compared to tasks that are dissimilar), preceding task feedback can provide more, and more clear options to avoid negative consequences (e.g., indications for improvement) in following tasks. So, we argue that task similarity will enhance the effects of negative feedback. Therefore, in study 3 we investigated the effects of task similarity on positive versus negative (social-evaluative) feedback from a robotic agent.

4 Experiment 3

4.1 Methods

Participants and design. One-hundred-and-twenty participants (72 men and 48 women) were randomly assigned to one of four experimental conditions: 2 (task similarity: high vs. low) x 2 (feedback type: positive vs. negative). In addition, each participant completed 16 washing trials, which composed the 16 levels of our third independent variable. All participants were native Dutch speakers.

Materials and procedure. The experimental procedure was identical to that of study 1, except that only social-evaluative feedback was given, and task similarity was manipulated. In a pretest, we asked 27 pretest participants to sort 16 different washing tasks on similarity. All participants in the current study performed the same 16 washing tasks, but, by changing the order of tasks based on the pretest, half the participants performed 16 relatively similar washing tasks, whereas the other half performed 16 relatively dissimilar washing tasks.

4.2 Results

The energy consumption score was submitted to a 2 (task similarity: high vs. low) x 2 (feedback type: positive vs. negative) x 16 (washing trials: 1 to 16) MANOVA, with the last variable within-subjects. Our expectancies were confirmed. That is, first, we found that participants who received negative (social) feedback consumed less electricity ($M = -.20$, $SD = .26$) than participants who received positive (social) feedback ($M = .02$, $SD = .32$), indicated by a main effect of feedback type, $F(1, 10635) = 515.60$, $p < .0001$. Second, we found the expected interaction effect of type of task similarity x feedback type, $F(1, 10635) = 5.90$, $p = .015$, indicating that task similarity enhances the effects of negative feedback. That is, results indicate that when tasks were relatively dissimilar, negative feedback led to the most savings ($M = -.18$, $SD = .27$, for negative feedback, versus $M = .02$, $SD = .32$ for positive feedback, $F(1, 10636) = 378.39$, $p < .0001$). But, importantly, the effects of negative feedback were larger when tasks were relatively similar ($M = -.24$, $SD = .25$, for negative feedback, versus $M = .02$, $SD = .32$ for positive feedback, $F(1, 10636) = 357.01$, $p < .0001$).

5 General Discussion

In general our findings demonstrate that people are sensitive to social feedback as provided by a robotic agent. Apparently, persuasive robotic agents are able to create behavior change among human users. Remarkably, our findings suggest that this effect is greater compared to the effects of (interactive) factual-evaluative feedback. The latter type of feedback can be considered as one of the most successful types of feedback employed earlier to induce energy conservation behavior (9).

In contrast to earlier work that focused on praise, our feedback intervention included both positive and negative feedback (Study 1). The effect of social feedback on energy conservation should therefore be considered as the joint effect of both positive as well as negative feedback. Interestingly however, our analysis on the level of single programming acts within trials, suggested that the direct influence of negative feedback on following programming choices was greater than the effect of the positive feedback. Study 2 demonstrated convincingly that providing single negative feedback is more effective than providing single positive feedback. Results of study 3 indicate that negative feedback is effective especially when tasks are relatively similar—as is the case in many of the day-to-day tasks people perform.

Moreover, it seemed as if the positive feedback encouraged participants to enhance their energy consumption. Thus, while people may feel pleased by a system that offers compliments to a user, this does not ensure behavior change. In particular, this may hold if a user has other goals to meet, like in our case getting clean laundry.

To our surprise, we did not find the expected effects of perceived agency. The participants in the low agency group conserved overall as much energy as those in the high agency group. Our tentative explanation is that the verbal manipulation we used to induce high or low agency was overruled by the direct experiences of the participants in their interactions with the iCat—an interesting future research issue.

Our present findings enhance our understanding of the persuasive potential at the behavioral level of embodied agents. They also suggest issues for further exploration such as the differential effects of positive and negative feedback, either single or combined. We propose that the stronger persuasive effect of negative (social) feedback might be strongly related to its efficaciousness. That is, negative feedback affords people to adapt their behavior to fit a situation and to avoid negative experiences. One of the consequences of this might be that negative feedback might lose its persuasive power when feedback is not situation and behavior specific. Finally, future research might also investigate the influence of perceived agency, for which further conceptualization and improved measures will be needed as well.

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Understanding Communication Patterns for Designing Robot Receptionist

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Abstract. The interaction between human and robot is a critical issue for increasing the acceptance of robot as a companion in everyday life. Understanding the nature of communication pattern between human receptionists and visitors is essential in answering questions to facilitate the design of dialogue for a robot receptionist. **Methods:** A controlled observation which involved 6 receptionists and 10 visitors was carried out. Conversations between two parties were transcribed and coded with Interaction Process Analysis coding scheme, and keyword and dialog pattern were analyzed subsequently. **Results and Discussions:** Some frequently used terms and patterns of communication were found during the conversations. One of the key findings is the importance of differentiation of pragmatic and literal meanings of a statement in designing a dialogue for a robot receptionist. Suggested keywords could be used as a reference for similar statements while a robot receptionist is suggested to adopt some of the communication patterns found in the conversations. **Future Works:** Communications are typically complicated and this study can be served as a pilot in establishing a guideline for designing dialogues for robot receptionists.

Keywords: receptionist robot, human-robot interaction, conversation analysis, Interaction Process Analysis.

1 Introduction

Although linguists treat language as a set of principles that specify the relations between a sequence of sounds and a sequence of meanings--to its users, what is most significant about language is its versatility as a medium for communication. All animal species communicate, but none achieve the precision and flexibility that characterizes human communication, a capacity due in large part to the uniquely human ability to use language [1], [2], [3]. For humans, communication is a complicated process involving a number of systems that work in collaboration. Although people typically communicate with relative ease, it's not entirely clear how they do it.

The focus of this paper is on the content and manner that make communication possible. Hence the goal of this study is to understand what factors constitute an intuitive and easy communication between the human and robot by looking at the verbal communication. It is also hoped that we can improve human robot interaction through designing communication dialogues for the robot receptionist. In general, a receptionist should be hospitable by greeting visitors warmly, be attentive to visitors' queries and provide assistance to the visitors in a pleasant manner. However, the characteristics of communication between human and robot are not investigated with enough detail. Since the communication between receptionist and visitors is not only for delivering the information requested by visitor, but also providing pleasant experience and good impression to the visitor, it is important to understand the communication process as a whole.

An experimental study was conducted to find out whether the robot should exhibit characteristic or traits found in a human receptionist. The study also examined keywords and pattern of communication used during the conversation between individuals. Through the conversation analysis, we identified areas such as how explanations and directions were presented by the receptionist, as well as communication patterns derived in order to complete the tasks. These behavioral patterns could allow future visitors to identify intuitive and familiar features when they interact with a robot receptionist.

2 Literature Review

Human-robot interaction is the study of interactions between humans and robots, where robots are treated as artificial agents with capacities of perception and action in the physical world. Historically, their use has been generalized in factories, but nowadays robots have the potential to be in application domains such as search and rescue, entertainment, hospital care and even as a receptionist. These new domains of applications imply a closer interaction with the user.

Robots that work in public settings raise some challenging design questions. To be successful in imparting guidance or answering questions, they must elicit cooperation from busy workers or visitors who are total strangers [4]. Furthermore, these interactions are likely to occur in the presence of others. Because people care about their self presentation to others in public [5], if they feel nervous or embarrassed during the interactions with robots, those feelings may negatively impact their willingness to cooperate. In order to make the interaction more comfortable, we sought to first understand communication patterns between two parties.

There are many characterizations of the ways language functions as a medium for communication, but the major ways are captured by four models or paradigms [6]; encoding-decoding paradigm, intentionalist paradigm, perspective-taking paradigm, and dialogic paradigm.

- **Encoding and Decoding:** Language often is described as a code that uses words, phrases and sentences to convey meanings. The Encoding-Decoding approach to language conceives of communication as a process in which speakers encode

their ideas in words, phrases and sentences, and listeners decode these signals in order to recover the underlying ideas.

- **Communicative Intentions:** There is abundant evidence to support *Intentionalist* view of language use. Listeners demonstrate considerable mental agility in divining speakers' communicative intentions. Identifying another's communicative intention is not always a simple or straightforward matter, in part because people do not always perceive the world in the same way [7].
- **Perspective-Taking:** To accommodate discrepancies in perspective, communicators must take each other's perspectives into account when they formulate and interpret utterances. The process is most readily illustrated spatial perspective-taking [8].
- **Dialogism:** Producing spontaneous speech requires the speaker to perform two cognitively demanding tasks simultaneously: conceptualizing the information to be conveyed, and formulating a verbal message that is capable of conveying it. The number and complexity of the factors that must be taken into account is dauntingly large [9].

Especially, social robots are expected to behave and communicate like human, the verbal emotions is important in communication other than the visual way of expressing emotions. Bull and Connelly (1985) have suggested that a person with a good social communication skill tends to receive a better impression [10]. They evaluated that students were found to be more attractive when they had better conversation ability. Pena and Hancock (2006) added that the videogames today involved social interaction, where people communicate and socialize with each other during the games [11]. Thus, the importance that the social robot has the ability to communicate well has further increased.

3 Methods

This experiment was conducted at a usability laboratory for the purpose of observing natural response and reaction between a visitor and receptionist, and identifying pattern of verbal communication such as speech, response and phrases.

3.1 Participants

Total number of 10 full time staffs, 7 male and 3 female, from the Institute for Info-comm Research (I²R) participated as the subjects in the experiment. 6 of them are Chinese, 3 of them are Indians and 1 of them is Caucasian and almost all of them (except 1) marked their most frequently used language as "English". The range of their age varies from 18 to 50 years old. Three of them are between 18-25 years old, one of them is between 26-30 years old, four out of the ten participants' ages are between 31-40 years old and two of them fall in the age range of 41-50 years old.

3.2 Procedures and Experimental Design

Three representative scenarios were designed for the experiment which can represent typical task of receptionist. The first scenario involved in handling appointment where the visitor informed the receptionist about a meeting with an appointed staff and

expressed his/her intention of meeting the person. The second scenario was about information query where the visitor asked about a particular location in the building. In this scenario, the visitor would ask about other facilities, such as swimming pool. The third scenario involved in taxi booking where the visitor would request a taxi to the airport.

The participants were instructed to carry out their role based on descriptions presented to them. A total of 10 respondents were invited to participate in this study to play the role of the visitor. We also appointed 6 personnel to play the role of the receptionist who had previous experience of working as a receptionist (6mo – 2 years). Information materials, such as, telephone contact list, description of facilities and a telephone were provided to the participating receptionist. They were also asked to respond to the scenarios as how they would normally do in their daily course of work. All 10 respondents who acted as the “visitors” were briefed on a specific scenario before proceeding into the user study room for the observations. After completing each scenario, they would exit the user study room to read the description for the next scenario. After completing all 3 scenarios, they were asked to feedback on their experiences during the actual study. Each session lasted about 30 minutes.

The inter-participant variability between each “receptionist”, including different pattern of communication, personality, tone, and accent, is known as the blocking factor in this experiment. The entire study and the sessions were recorded on video. From the videos, the dialogues were transcribed for further analysis. The individual utterance of the 10 dialogue transcriptions were further analyzed with categorization using the modified IPA coding scheme. In the experiment, the authors are much interested in the pragmatic meanings of the conversations. Hence, each utterance will be categorized with its pragmatic meaning rather than its literal meaning.

3.3 Measurement

To examine how this communication can take place, interaction process analysis (IPA) is used. The purpose of the IPA system is to identify record the socio-emotional and task-orientated communications between individuals [12]. This analysis consists of 12 categories for communication, as shown in Table 1. Within the 12 categories, six of the categories contain socio-emotional messages, where (1), (2), and (3) are positive messages, while (10), (11) and (12) are negative messages. The other six types of messages are task-oriented messages, which are questions and answers that enable the completion of a task [11]. Beside the 12 original categories in the IPA coding scheme, the authors created a new category 13, which will be coded when the receptionists are talking to the 3rd party, mainly over the phone. The reason of having the category 13 is because the visitors were still able to capture some pieces of information while the receptionists were talking to the 3rd party.

4 Result and Discussion

The utterances of both the receptionists and visitors were coded by two coders with IPA coding scheme. A total of 783 statements were recorded, transcribed, and coded

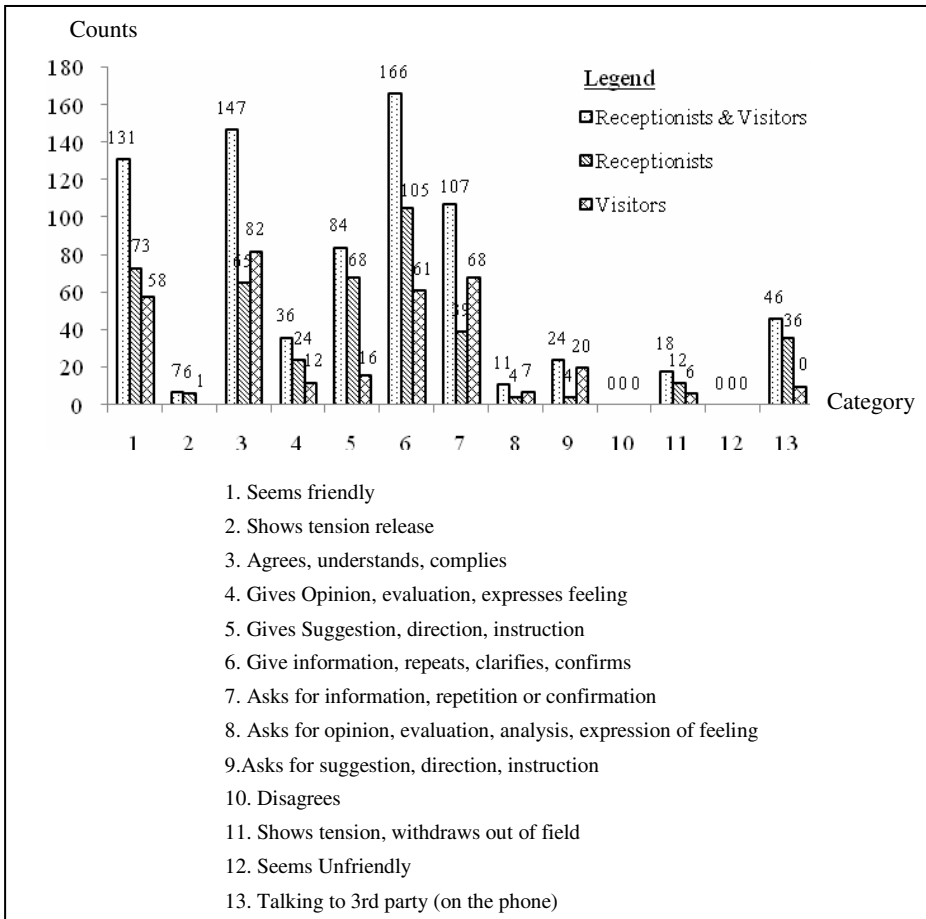


Fig. 1. Counts of utterances in each category made by the receptionists and the visitors

with IPA coding scheme in all the 10 sessions. Figure 1 shows the cumulated counts of each category coded in the entire sample.

The IPA coding is done by two evaluators independently, and any disagreement on coding are resolved through a group discussion with two evaluators. The overall result of both receptionists and visitors coding shows that there is no utterance coded as category 10 (disagrees) and category 12 (seems unfriendly). Such a result implies that the conversations between receptionist and visitor are generally held in a friendly and polite manner and seldom should there be any disagreement.

Communicative exchanges that relied exclusively on such an arrangement would impose a heavy cognitive burden on the participants. Probably because we do it so well, we seldom appreciate how complicated a process communication is. Close examination of what actually is said in conversations reveals that it is seldom an orderly process in which participants alternate in the roles of speaker and listener. Rather, sentences often trail off inconclusively or are left dangling incomplete, listeners

interrupt to ask questions, interject comments and finish sentences, topics change abruptly and unpredictably, and what is left unsaid may convey more than what is explicitly stated. It would be a mistake to regard such conversational speech as a defective version of some ideal form. Rather, these apparent aberrations reflect the way conversation operates as a communicative process.

4.1 Utterances of the Receptionists

The category of giving information, repeating the conveyed message, giving clarification and confirmation appeared 105 times (24.1%) of total utterances of the receptionists. The highest count of this category in the utterances of the receptionists indicates the main task of a receptionist is actually to provide information and clarification to the visitors upon their queries.

The patterns of the receptionists conveying information to the visitors are pretty much similar; they are simple, clear and direct. It implies that the design of the dialogue of a robot receptionist in conveying information to the visitors should be always simple, clear and direct. Also, category 6 was sometimes found together with category 5 where receptionists are giving instructions or providing directions to the visitors. For example, *"It is both connect. Once you are on top, you can actually walk around, and you will see that actually they are linked."* and *"Oh, Skygardens are on the roof top, ah, not in this building, but in the North Connexive Office. You can take the lift up the top floor"*. Such an implication suggests designing a dialogue of giving instruction and direction may be better to start with providing general information to the visitor. It could enhance the visitors' understanding of instructions by providing them with a big picture beforehand.

"Seems friendly" (category 1) was coded 73 times (16.7%) as the second highest coded category in the utterances of the receptionists. There are a few situations that the receptionists would express friendliness during the conversations, for example, greeting the visitors, offering helps to them, expressing gratitude at the end of the conversations, responding to the visitors' politeness and closing the conversations.

The common statements that the receptionists used in category 1 contain the purpose of greetings/starting the conversation (45.2%; 33), closing conversations (16.4%; 12), expressing gratitude (15.1%; 11), responding to thanks (9.6%; 7), offering help (8.2%; 6), and others (5.5%; 4). The result can be used as a reference in designing the dialogues of a robot receptionist. It outlines when a receptionist should express friendliness and what should a receptionist say at the point of time.

"Giving instructions and directions" (category 5) was coded 68 times (15.6%) among the utterances of the receptionists. It was coded when the receptionists were giving suggestions, directions and instructions to the visitors. Normally, the statements in this category contain phrases such as, *"Why don't you"*, *"Please"*, *"You might want/or have to"*, and *"You can/need to"*. The main constructs of this category is to suggest a route or a direction to the visitors to specific location and to give instructions to the visitors for their further actions. Similar to "category 6" above, the utterances in this category were simple, clear and direct. Other than that, no general pattern could be found under this category.

“Agrees and showing passive acceptance” (Category 3) was coded 65 times, as much as 14.9% of total utterances of the receptionists. “Category 3” was commonly used by the receptionists when they were showing passive acceptance of the previous statements made by the visitors and their understanding of the requests or enquiries made by the visitors. Some of the frequently used phrasing in the conversations include “*Okay*” (45.6%; 31), “*Yah/Yeah* (13.2%; 9)”, “*Okay, sure*” (11.8%; 8), “*Yah, sure*” (7.4%; 5), “*Right/Alright*” (5.9%; 4), “*Sure*” (4.4%; 3), “*Yes*” (4.4%; 3), and others (7.4%; 5). The counts and percentages of commonly used terms in category 3 are summarized in the table below,

The common pattern in “category 6” shows that in prior to conveying information to the visitors, the receptionists would first of all confirm the acceptance of previous messages made by the visitors and pass the message after that. There are two common ways the receptionists used in the experiment to confirm their acceptance of messages from the visitors. They could confirm their acceptances of message by either reading back the key information in the previous utterance, for example “*Swimming facility. Let me see. Yes, we have a pool, but it is only opened to apartment guests.*” or using some facilitators such as “*ok, sure*” and “*yah*” to start their statements. It might be better to acknowledge the acceptance of information from the visitors before the robot receptionists should continue with its statement. Not only it can provide feedbacks to the visitors, also, it can be served as a tool to confirm the recognition of correct message.

4.2 Utterances of the Visitors

The IPA coding of visitors’ utterances shows that the 4 highest coded categories are category 3 (agrees, understands, complies), category 7 (asks for information, repetition or confirmation), category 6 (Give information, repeats, clarifies, confirms), and category 1 (Seems friendly).

“Agrees and showing passive acceptance” (Category 3) was coded when the visitors agree with, understand and comply with the suggestions or instructions given by the receptionists. It is coded 82 times, as much as 24% of the overall utterances made by the visitors. “Agrees and showing passive acceptance” (category 3) was used in a few situations, for example it was used by the visitors when they would like to acknowledge the acceptance of previous pieces of information given by the receptionists, and implicitly to show their passive acceptance to the suggestions or instructions given by the receptionists. Commonly used words found in this category include “*Okay*” (80.6%; 58), “*Yah*” (9.7%; 7), “*yes*” (5.6%; 3), and others (5.6%; 4). Table below shows the counts of frequently used words, the counts of words in this category and the percentages.

“Asking for information, clarification and confirmation” (category 7), was the second highest coded category in the utterances of the visitors. It was coded 68 times, playing a weightage of 19.9%, out of the total 341 utterances of the visitors. In the experiments, “category 7” was used by the visitors when they were asking for information about Sky Gardens and other related information such as the permission of entry of the gym and swimming pool in the building. Besides, category 7 was also

largely used when the visitors were seeking for confirmation of their understanding of information or direction. 7% (5 items) of the statements were used for confirmation, and 93% (66 items) of the statements were used for asking information.

When the visitors were asking for information, two types of pattern found in their statements: direct and indirect. Literal meanings of direct question comply with their pragmatic meanings. For example, when the visitor is asking “*Where is the swimming pool?*” means that he or she would like to know the location of the swimming pool. However, large amount of questions were not asked in a direct pattern, they were usually asked in an indirect question form, which the literal meaning does not comply with its pragmatic meaning. For example, when the visitor is asking “*Is there a swimming in this building?*”, pragmatically, it means that “*Can you show me the way the swimming pool?*” This is an unwritten rule that both the visitor and human receptionist will know. However, to a robot, it may not be as simple to understand the rule. Therefore, in the design of dialogue for a robot receptionist, the robot should be able to read into the pragmatic meaning of a statement in “category 7” conveyed by the visitors rather than just its literal meaning.

Also, before the visitors asked for information, they normally would like to provide some background information (i.e. “category 6”) for the receptionists. The background information can be served as an aid for the receptionist to have a more thorough understanding of their enquiries. For example, “*Err... I read from the internet that there is a Sky Garden in this building?*” Hence, it is possible for a robot receptionist to understand visitors’ queries from the prior information given by them.

“Giving information, confirmation and clarification” (category 6), was coded 61 times, as much as 17.9% of the overall statements made by the visitors. It was found in the conversations in a few of situations. Firstly, it can be found when the visitors are revealing their identities to the receptionists, for example, stating their names and where they come from (29%; 18). Besides, category 6 was also found when the visitors were stating their purpose of approaching the receptionist (71%; 44), for example, they need a book a taxi or their appointment details. The table below shows the purposes of the statements, examples, number of items, and percentages in each subcategory.

“Seems friendly” (Category 1) was coded 58 times (17%) of the overall utterances made by the visitors. It was coded when the visitors were expressing their friendliness to the receptionists. In general, there were a few situations, such as expressing gratitude (42.1%; 24), greetings (36.9%; 21), closing the conversation (17.5%; 10), and others (3.5%; 2), that the visitors would show their either their politeness or friendliness.

4.3 Pattern of Communications

Other than finding keywords and recognizing common communication patterns from the coded conversations, using coding scheme to analyze conversations tell us the quality of a given answer. For example, a statement which is asking for information (category 7) ideally should be followed by a statement which is giving information (category 6). Similar to this, a statement of asking directions and instructions ideally

should be answered with a statement of giving instructions and directions. A matching of the category of statements can be viewed as a basic guideline for a robot receptionist to provide a more appropriate answer to the visitors.

One reason people are able to communicate as well as they do in such adverse circumstances is that the exquisite responsiveness of conversation and similar highly interactive forms permits them to formulate messages that are closely attuned to each others' immediate knowledge and perspectives, which reduces the cognitive demands of production and comprehension. The participant who at a given moment occupies the role of speaker can determine virtually instantaneously whether the addressee has identified communicative intentions correctly. Simultaneously the addressee can reveal the nature of his or her understanding as it develops, and in this manner guide the future production of the speaker.

5 Conclusion

In recent years, with the maturity of technology and increasing needs of social companions, the research of social robotics becomes a hot topic. As such, the usage of robots is diverted from the traditional industry and scientific fields to also the field of healthcare, social and entertainment. For the social robots such as robot receptionists, rather than speed and accuracy, their performances are much related to the other attributes such as user's satisfactions and interactivity. In designing a robot receptionist, designers are interested to know how a robot receptionist should talk and communicate with the visitors.

From the experiment capturing the communications between human receptionists and visitors, a couple of general patterns in communication were found. For example, in prior to conveying information to the visitors, it is common that a receptionist would acknowledge the acceptance of previous statements by either reading back the key points in the previous statements or using facilitators such as "*okay*" and "*yes*". Also, a receptionist would like to give general information to the visitor before they started directing the visitors. These patterns found can be used as design implications for a robot receptionist. Besides, the result of analysis could also be a reference for designers to know 'when' and 'what' to say for a robot receptionist to mimic a human receptionist. For example, when a robot receptionist should express friendliness and what a robot receptionist should say to make itself seems friendly. With a combination of accuracy and reliability of robots and excellent communication skills, a robot receptionist is expected to perform as good as human receptionist in the near future.

Acknowledgements

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Do Social Robots Walk or Roll?

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Abstract. There is a growing trend of social robots to move into the human environment. This research is set up to find the trends within social robotic designs. A sample of social robotic designs is drawn to investigate on whether there are more legged social robots than social robots with wheeled. In addition we investigate whether social robots use legs or wheels for locomotion, and which continent produces the most social robotic designs. The the results show that there are more legged robots, most robots use them for locomotion and Asia is the continent that produces most social robots. It can be concluded that there is a trend that social robots are more and more designed to have legs instead of wheels. Asia has more different social robotic designs to cater to different needs of human.

Keywords: social robots, leg, wheel, locomotion, continents.

1 Introduction

Social robots are playing an important part in our future society. Already today, service robots outnumber industrial robots [3]. They are intended to entertain, educate and care for their users. One of the main design questions for these types of robots is if they should walk or roll. Walking robots can operate easier in an environment that is originally designed for human beings. Stairs, steps and the variety of floor coverings do not bother them too much. However, rolling is a much more reliable form of locomotion since the robots do not need to keep their balance. Since the field of social robotics has been confronted with this problem for some time, it appears useful to investigate how the robotic developers have overcome it.

A social robot is an autonomous robot that interacts and communicates with humans or other autonomous physical agents by following social behaviours and rules attached to its role [2]. This definition suggests that a social robot must have a physical embodiment. We followed this definition and did not include

screen based agents, industrial robots or military robots. Surveys about the field of social robotics date back to already 2001 [1], meaning that first robots can already be expected to appear 15 years ago. We therefore included robots that were at least available since 1995.

It is very difficult to collect information about the absolute number of social robots that were released. Arguably, Aibo was the most sold social robot so far with 140.000 units sold [4]. We therefore focused not on the absolute number of robots, but on the count of different robotic designs. We did not require the social robot to be commercially available in order to be considered for this survey, since many social robots never left the research laboratories. It is sufficient if only one example robot was ever built. Thus to identify the trends of social robots, the following questions formed the focus of the research:

1. Are there more social robotic designs with legs or wheels?
2. Are the legs or wheels of the social robots used for locomotion?
3. Which continents develop more social robots?

2 Method

2.1 Data Gathering

A sample size of 106 social robots was randomly gathered through a web search. Only general keywords like “Robots” and “Social Robots” were used as search terms in different search engines, such as Bing, Google and Yahoo. Specific keywords like: “robots + legs”, “humanoid + robots” or “wheels + robots” were not used, since they would have biased the sample of the search results. We assume that the 106 found social robots represent a random sample of social robots. We then manually inspected the robotic designs and recorded their features in a spreadsheet. The following features were extracted:

- Ability to perform locomotion
- If the robot has legs and how many
- If the robot has wheels and how many
- Country origin of the robot
- Creator of the robot
- Web or book references

The robots that were included in the analyses are listed in table 1:

2.2 Categorization

Based on the collected raw data, the robots are categorized into four categories: With Legs only, With Wheels only, With Both or With None. Their definitions as follows:

Legs. Any limbs that have contact with the ground regardless of ability to perform locomotion. Example: Asimo [6]

Table 1. Robots included in the analyses

Actroid DER 2	i-Qbot	Rave Raffe
Aibo	iCat	Reddy
Aida	iCub	reem-A
AirJelly	Irobot	Reem-B
ApriPoko	IsaacRobot	Ri-Jo
ASIMO	Joe Robot	RIBA
Autom	Joebot	Robin
BigDog	Kande and Turin	Roborover
Callo	KASPAR	Robosapien
CB2	Keepon	Robosapien V2
CHARLI	Keiko	Robot Cub
coco	KHR-1	Robot Jockey
Doki	Kismet	Robovie-IV
doppelganger robot	Kiyomori	Rovio
Dream Parrot	Kobian	Rubot
Dyson Robotic Vacuum Cleaner	Konan	Serviboy
emuu	Kozirou and Kotarou	Sessha and Soregashi
ERS-311	Land Walker	Spykee
EveR1	Leonardo	Steam Walker
EveR2-Muse	Liangliang	T-Bot
evolta	Maggie	T2-5
Femisapien	Mahru	Tamanoi Vinegar Robot
flame	Mahru-R	Tiro
Flexible Spine Robot	Mahru-Z	Tofu
Flexible-jointed Robot	MANOI-AT01	Topio
G-Dog	MANOI-PF01	Toyota's Robot Quartet Band
Germinoid	Miss Repliee Q1	Toyota's Running Humanoid Robot
Gil and Gil Son tan	Mr. Personality	Tri-Bot
GR-001	nao	Twendy-One
guroo	Nexi	USB robot webcam
gymnast robot	Paro	WABIAN-2R
HOAP-3	Plen	WE-4RII
HRP-2	Popo	Wine-Bot
HRP-4C	Probo	Wrex The Dawg
Huggable	QRIO	Zeno
I-FAIRY Robot		

Wheels. Appears to have a circular frame or disk arranged to revolve on an axis regardless of ability to perform locomotion. Example: Papero [5]

Both. With properties of Legs and Wheels regardless of the ability to perform locomotion

None. Has neither the properties of legs and wheels regardless of ability to perform locomotion. Example: Paro [7]

In addition, the robots are also categorized into their ability to perform locomotion, which means the act or power of moving from place to place. This is to find the relation between the use of legs or wheels for locomotion. An example of a robot that has human like legs yet unable to walk is Geminoid HR1 [3]. Based

on the country origin of the social robots, they are also categorized into their respective continents based on the following definitions:

America. Consist of 35 sovereign states (North & South America)

Europe. Consist of 47 sovereign states (Northern, Eastern, Southern and Western Europe)

Asia. Consist of 47 sovereign states (North, South, East, West, Central Asia and South East Asia)

Others. Any countries that does not fall in any of the three continent mention about (Asia, America & Europe)

As there were only two out of hundred and six robot designs that were made in Australia or Africa, thats why the focus was set on comparing the three major continents of robot creators, and labeling the rest as “others”.

3 Results

3.1 Robots with Legs or Wheels

From the sample of 106 robots, 63 robots had only legs, which covered about 59% of the total robots (see Figure 1). To determine whether there are more robots with legs or wheels, the number of robots with legs only and wheels only are compared.

Based on the data, there are 20 social robotic designs with wheels, while the other 63 robotics designs are with legs. We calculated a 99% confidence interval around the sample proportion for the legged robots of $\frac{63}{83} = 0.759 : Pro[0.638$

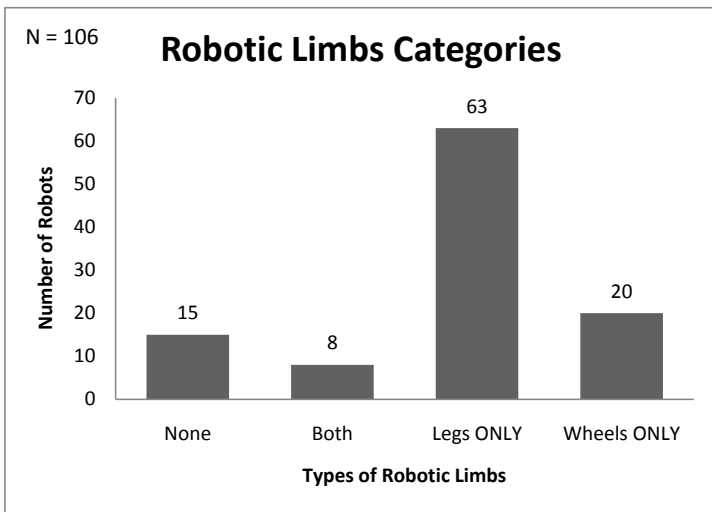


Fig. 1. Number of robots with different robotic limbs

$< II < 0.880] = 0.99$. The confidence interval does not include the value of 0.5 and we can therefore conclude with 99% certainty that there are significantly more robotic designs with legs than with wheels.

We also collected information about the number of legs and wheels per robot. The mean number of legs or wheels is 2.2 and 3.21 respectively (see Figure 2). It is thus more common for a robot with legs to have two legs. This shows that social robots with legs are likely to be made with two to imitate the action of human walking. On the other hand, robots with wheels are likely to have 3 wheels: two for movement and one for balance.

3.2 Ability of Robots to Perform Locomotion

The relationship between the ability of the robot to perform locomotion and whether it has either legs or wheels to perform is determined in Figure 3, which shows that 78 out of 91 of the robots with either legs or wheels can use their legs/wheels to perform locomotion.

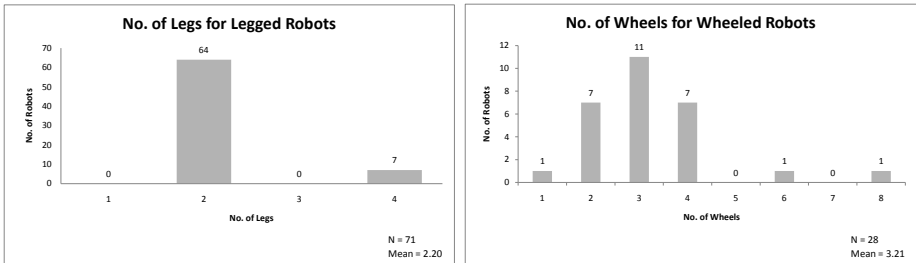


Fig. 2. Count of number of wheels or legs per robot

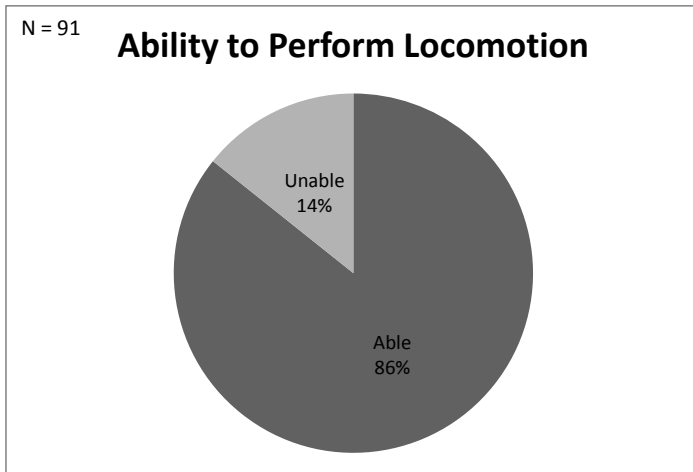


Fig. 3. Proportion of robots with legs or wheels that can perform locomotion

Based on the data, we constructed a 95% confidence interval around the sample proportion of $\frac{78}{91} = 0.857$: $Pro[0.785 < \Pi < 0.929] = 0.99$. Since 0.5 is not within the confidence interval, we can conclude that there are significantly more social robots that use locomotion than robots that do not.

3.3 Geographic Distribution

The pie-chart below shows an overview of which continent contributes the most different robot designs (see Figure 4). The chart shows that, Asia covers 55% of the whole sample. This is largely contributed by one of the worlds top robot creator, Japan. Japan alone covers 42% of the total sample, Korea follows with 10%. With Japan and Korea in the top three, Asia may continue to hold the status of being the top robot-creating continent.

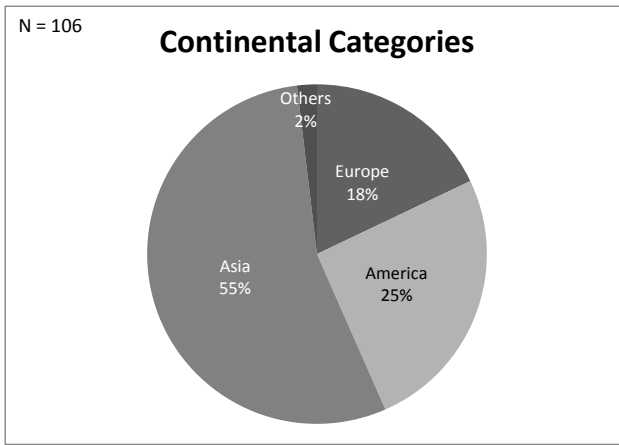


Fig. 4. Proportion of robotic designs based on their continent origin

4 Conclusions

When it comes to deciding whether to use legs or wheels for social robots, each of them definitely has strong advantages of their own. Wheels are more stable and balance in terms of ability to perform locomotion and operation. However, social robots are supposed to be made to interact with humans. This would mean that they are operating in an environment designed for humans with legs. Thus legged robots have the advantage of ease of moving in and interacting with the human environment. From the data, there is a 99% certainty that there are more than 50% of robots with legs. We can also be 95% sure that if the robots have either legs or wheels or both, most of them can perform locomotion. So the limbs or wheels are less likely to be for aesthetical purpose, but also used for locomotion. From these fact mentioned above, there is a trend that social

robots tend to have legs that can locomotion. So it is likely that social robots in future will be built with legs in order to integrate into the human environment. It also shows that interaction with humans is no longer the only function of social robots; they must also have the ability to perform locomotion in a environment based on human movement.

This study also has some limitations. We were not able to reliably record the date of the initial release of the robotic designs. We could therefore not compile a time line that would give us some insights into the development of social robots over time. From a qualitative point of view we were under the impression that older robot design tended to use wheels, and that more recent robots tried to move into the direction of humanoids.

We are also not able to address the question if users would have a preference for legged or wheeled robots. Neither can we address the question what aesthetic implications the use of legs or wheels have.

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Synthetic Skins with Humanlike Warmth

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Abstract. Synthetic skins with humanlike characteristics, such as a warm touch, may be able to ease the social stigma associated with the use of prosthetic hands by enabling the user to conceal its usage during social touching situations. Similarly for social robotics, artificial hands with a warm touch have the potential to provide touch that can give comfort and care for humans. With the aim of replicating the warmth of human skin, this paper describes (i) the experiments on obtaining the human skin temperature at the forearm, palm and finger, (ii) embedding and testing a flexible heating element on two types of synthetic skins and (iii) implementing a power control scheme using the pulse-width modulation to overcome the limitations of operating at different voltage levels and sources. Results show that the surface temperature of the human skin can be replicated on the synthetic skins.

Keywords: Synthetic skin, social robotics, warm skin, rehabilitation robotics, prosthetics.

1 Introduction

Touch is a fundamental human need. The human touch promotes physical, emotional, social and spiritual comfort [1]. Through touch, distinct emotions such as anger, fear, disgust, love, gratitude and sympathy can be communicated [2]. However, these benefits are lost in the case of a loss of an upper limb that may be due to illness, accident or war. Likewise, it could also be possible to enable a social robot to be perceived as communicating emotions associated to comfort and care when equipped with capabilities for humanlike social touching.

This paper addresses the possibility of replicating the skin surface temperature of the human skin on synthetic skins. Toward this end, we conducted experiments to obtain the surface temperature of the human skin at the forearm, palm and fingertip. Then, we embedded a heating element on samples of synthetic skins and varied the voltage inputs to reach the typical range of human skin temperature. Lastly, we implemented a power control scheme to overcome the limitations of operating at different voltage levels and sources.

Previous works have been mainly focused on tactile sensing of surface temperatures for robotics applications [3-8] and the replication of temperatures through tactile displays for teleoperation purposes [9-12]. To the best of authors' knowledge, no

research on replicating the human skin's warmth on synthetic skins has been reported. With the emergence of prosthetic hands that can be controlled with the user's thoughts [13-16], we surmise that synthetic skins with similarities to the softness and warmth of the human skin will be needed as it is human nature to touch and be touched, while being able to conceal the stigma from the loss of limbs. Our previous works on synthetic skins with humanlike skin compliance have been earlier presented in [17-20].

Traditionally, it was believed that the thermal sensitivity of the human skin consisted of isolated cold and warm spots with a single specific receptor beneath each spot which was assumed to have a one-to-one relationship with the quality of sensation by the spot of skin above it [21]. This view was first introduced by Blix [22], and Goldscheider [23]. In 1941, Jenkins [24, 25], provided psychological evidence that sensory fields are in the form of areas of highly sensitivity surrounded by areas of decreasing sensitivity. Later, Melzack et al [21], investigated the distributions of sensitivity by mapping large areas of skin using the stimulators, with their diameter and tip temperature controlled, to verify the evidence of overlapping receptive fields. Their studies showed that the distribution is in the form of large sensory fields with a variety of sizes and shapes. It was also observed that the spatial properties of stimuli play an important role in determining the quality of cutaneous experience [21].

It is known that the local temperature of the skin is dependent on a variety of factors, such as environmental and weather conditions, human internal metabolism, blood flow, and etc. According to Sakoi and co-workers [26], the air temperature, thermal radiation, air velocity, humidity, clothing and activity are six well known factors that influence the human thermal state in steady state and uniform thermal environments [26]. The skin temperature can also be different for people of different age, sex, and weight, as well as, different internal conditions. For example, when people are in a state of stress, the finger skin temperature decreases [27]. This is apparent when we shake hands with people who are nervous.

Previously, some experiments were accomplished in order to investigate thermal comfort for the human body (both whole and local comfort) as well as the local skin temperature. Sakoi et al [26] carried out these experiments by setting up a booth in climate chambers with controlled environmental conditions. The experimental data were measured for different males and females with different clothing, while they were all requested to refrain from eating one hour prior to experiments [26]. It was shown that depending on the environmental thermal non-uniformity, the local skin temperature changes even if the mean skin temperature remains almost the same. Furthermore, the mean value of the skin temperature of the whole body was reported to be ranged from 32.6 to 35 °C and the peak of overall thermal comfort was located around 33.5°C of the mean skin temperature [26]. It is also worth mentioning that one of the main results of this paper was the insufficiency of a mean skin temperature for describing the overall thermal comfort in non-uniform thermal conditions. Thus, in order to have a better picture of human thermal comfort, skin temperature distribution is reported to be essential [26].

With our stated objectives and leveraging on the existing knowledge on human skin warmth, this paper has been organized as follows. Section 2, describes the materials and the methods. Section 3 presents the results and discussions. Finally, Section 4 provides the conclusions and the future directions.

2 Materials and Methods

This section has been divided into two parts. In the first part, the experiments to measure the human skin temperature are described and then followed by the description of the heating element, synthetic skin materials and the procedures to replicate the measured human temperature data.

2.1 Human Skin Temperature

The local temperature of human skin is different in various parts of the body and varies according to different conditions; among them is the ambient temperature. When a person enters a room, the body starts to adapt its temperature until it reaches a steady state with time, which depends on individual's internal situation, age, sex, etc. In this regard, we measured the skin temperature on the forearm, palm and index finger to determine the typical values that will serve as target data for our synthetic skins.

Experimental Setup. Six subjects (4 males and 2 females) were selected for the experiments in two different conditions. In the first one, the subjects' hand temperatures were measured upon entering the room for different room temperatures (20, 25 and 32 °C) using a k-type thermocouple based precision thermometer (FLUKE 52-II). In the second one, the same experiment was repeated for the subjects after 30 minutes of entering the room which allowed the subjects' body temperature to stabilize. For each subject, in each room temperature, and on each active part of the hand, the measurement is repeated four times with intervals of two minutes. It should be mentioned that in this setup, it was assumed that the skin temperature does not vary due to sudden metabolic activities and blood flow.

Human Skin Temperature Response. The human skin temperature response with respect to the both skin materials was compared. Both of skin material and human were brought from a temperature of 32 °C suddenly into a room maintained at 20 °C and the rate at which the temperature decreased was recorded to check whether there is a need for a cooling element in addition to the heater.

2.2 Materials

Heating Element. A flexible polyimide heating element (HK5200R5. 2L12B, Minco, Singapore) was selected to duplicate the human skin temperature for synthetic skin. This heating element dimensions were chosen to be 50 mm × 6.5 mm. Then it was coupled to the skin material using a pressure sensitive adhesive (PSA-Acrylic, Minco, Singapore). The resulting resistance of the heating element was measured to be 5.1 ohms.

Skin Material. Samples of silicone (GLS 40, Prochima, s.n.c., Italy) and polyurethane (Poly 74-45, Polytek Devt Corp, USA) which were previously characterized for their mechanical behavior [19, 28] and used as skins of prosthetic and robotic fingers [29, 30] were selected for experiments. Each skin material was fabricated in a rectangular shape with the dimensions of 50 mm × 35 mm and thickness of 3 mm as shown in Fig. 1 (Left).

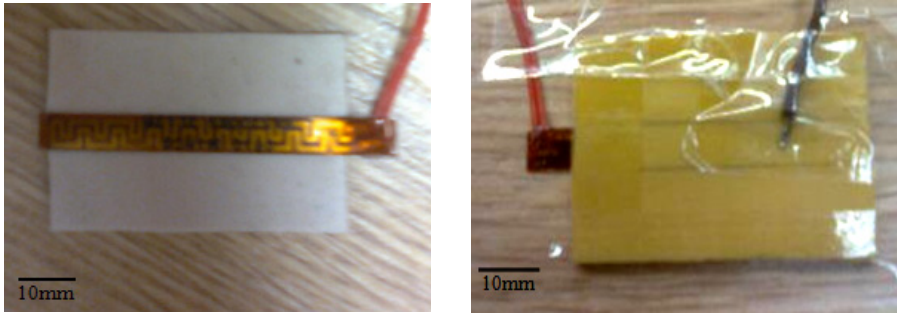


Fig. 1. (Left) The underside view of the silicone skin material with the flexible heating element. (Right) The polyurethane skin material with the heating element at the bottom and the thermocouple at the skin surface.

Experimental Setup. The experiment consisted of the heating element, the skin materials (silicone and polyurethane), a k-type thermocouple based precision thermometer, split timer and a power supply. The heating element was coupled to the skin material as shown in Fig. 1 (Left) using a pressure sensitive adhesive. The other side of the heating element was insulated using wood which ensures the maximum heat transfer to the skin material. The heating element was powered from a DC source and the thermocouple was placed on the skin material directly above the heating element.

Experimental Method. The experiment was conducted in an isolated room which temperature was maintained at 20°C. The skin material was allowed to settle down to a constant temperature and it was measured to be 23°C. The heating element was turned on at time $t = 0$ second from a DC power supply. The temperature of the skin material exactly above the heating element was monitored as shown in Fig. 1 (Right). The time instant at which the temperature crosses integral temperature values (in °C) was recorded and tabulated. The experiment was repeated for different input voltage supplies to the heating element.

Power Control Using PWM. As the resistance of the heating element is constant, the square of the voltage applied across its terminals is directly proportional to the power dissipated as heat. Hence, we have,

$$P_{heat} = \frac{V^2}{R} \quad (1)$$

where P_{heat} is the power dissipated as heat, V shows the voltage applied across the heating element, and R represents the resistance of the heating element.

In order to regulate the dissipated heat, the heating element needs a variable voltage supply. Practical implementation in a prosthetic device demands a compact power source such as a battery. Thus, a method needs to be devised to control the power delivered to the heating element from a fixed voltage source such as a battery. The pulse-width modulation (PWM) scheme facilitates such implementation by controlling

the average power delivered from a fixed source. The average power delivered from the source can be varied by varying the PWM duty cycle ratio (D) of the modulator.

$$P_{heat} = \left(\frac{V^2}{R} \right) D \quad (2)$$

From (1) and (2) we can derive the relation between the duty cycle and the equivalent voltage (V_{eq}).

$$V_{eq} = V \sqrt{D} \quad (3)$$

The PWM heating system when operating from a fixed voltage V and duty cycle ratio D dissipates power equal to that dissipated by the heating element when driven from a DC Voltage supply of V_{eq} . To validate this, the experimental setup was driven using a 4V supply modulated with a duty cycle of 5/8 at a frequency of 0.02 Hz. The temperature of the skin element directly above the heating element was recorded. The same set up was then driven using its equivalent Voltage (V_{eq} calculated using (3) to be 3.2 V) from a DC Power Supply and the time instants at which the temperature crosses integral values (in °C) were noted.

3 Results and Discussions

3.1 Human Skin Temperature

Fig. 2 shows the mean values of temperatures for the forearm, palm and index finger of six subjects at three different room temperatures. The top row shows the temperature data as the subjects enter the temperature-controlled room. The bottom row shows the data obtained after 30 minutes. The skin temperatures ranged from 21.3 to 36.5 °C. The local skin temperature of various parts of the hand varies according to the room temperature. Among the selected locations, the lowest skin surface temperatures were recorded at the index finger. In accordance to earlier reports, our experimental data show that the temperature distribution is different for people of different weight, age, and sex.

3.2 Materials

Input voltages of 1V, 1.5V, 1.8V and 2V were set for the heaters embedded on the silicone material sample. For polyurethane, input voltages of 1V, 1.5V, 2V and 2.5V were applied. Figs. 3 and 4 depict the temperature rise that corresponds to the changes in the input voltages.

Several observations can be made from the results of Figs. 3 and 4. First, it can be seen that the temperature curves have a steep initial climb, which stabilizes with time. This indicates that most of the heat is absorbed initially by the skin material to raise its temperature and as time passes, the skin element attains a steady state temperature and the heat supplied to the heating element is radiated into the surroundings.

Second, we can observe that the voltage range of 1V to 2V is sufficient to replicate the range of human skin temperatures as shown in Fig. 3.

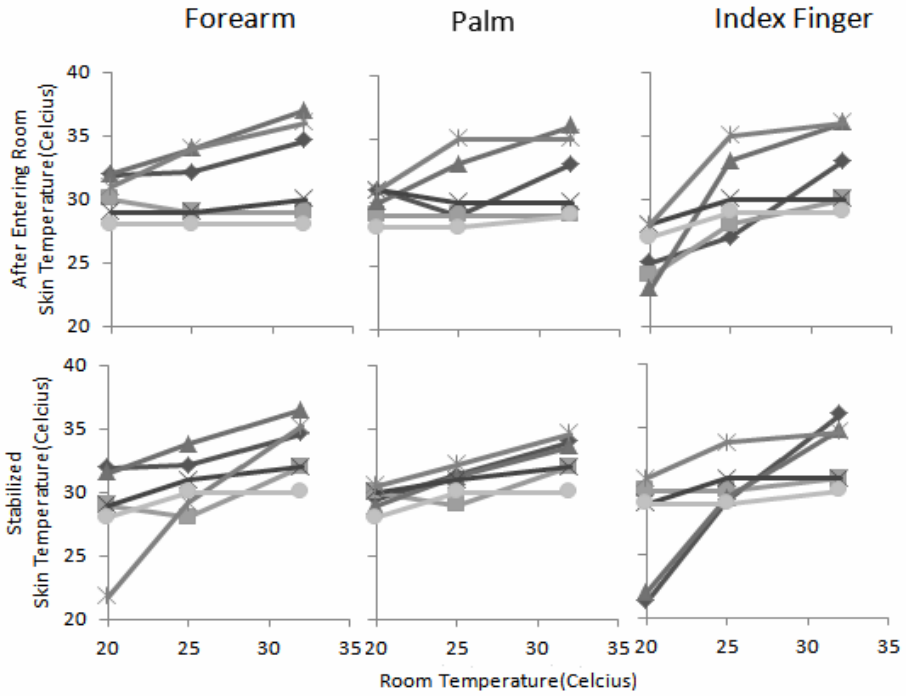


Fig. 2. Forearm, palm, and index finger skin temperature vs. room temperature for six subjects in two conditions (top row: temperature taken upon entry to the room and bottom row: after the subject has stayed in the room for 30 minutes)

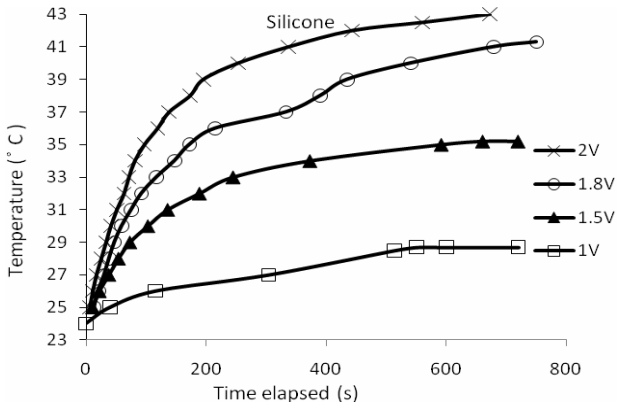


Fig. 3. Silicone surface Temperature vs. time at various input voltages

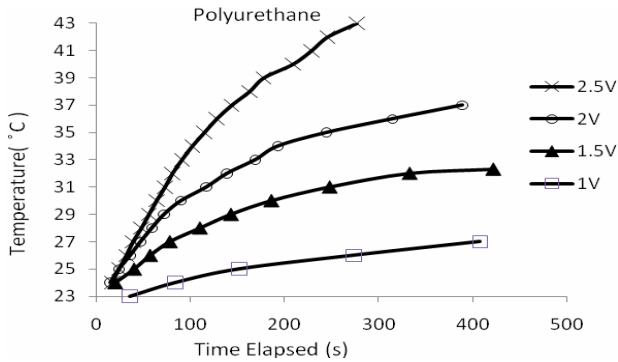


Fig. 4. Polyurethane surface temperature vs. time at various input voltages

Third, we can infer that when the power output from the heating element is higher, it takes a longer time to reach steady state temperatures on the skin material. Hence the time taken for establishing a given temperature (response time) varies with the target temperature. To achieve specific response times for a given temperature, constant voltages cannot be used. This calls for a different powering scheme to power the heating element so as to mimic the human temperature response.

From the Fig. 5, we see that the PWM controlled heating element and the DC powered heating element (V_{eq}) have similar temperature variations. The PWM frequency was purposely set to a very low value (0.02Hz) in order to get a better understanding of the power averaging that it delivers. A closer look at the graph shows the temperature of the skin material tries to reach the temperature of the skin material heated using a fixed V_{eq} at the instances of time that differ by the time period (1/frequency) of PWM, thereby creating an averaging effect on the power delivered.

Since the heating elements are made using closely laid pattern of conducting material, a large sheet of heating element (as ones that can be used to heat a forearm) can have large parasitic capacitance. This limits the maximum frequency at which the

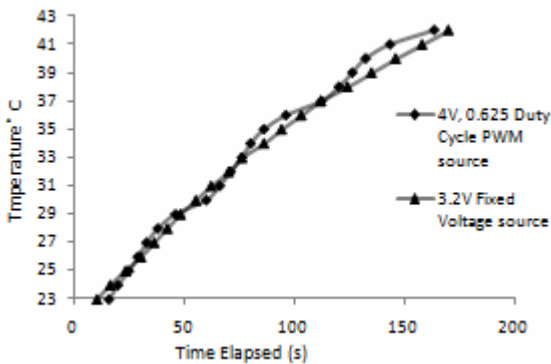


Fig. 5. Comparison of PWM controlled source and a fixed DC source for a heating element

PWM scheme can be operated. But since the human temperature response times are slow, the PWM frequency only needs to be less than a few KHz in most cases and thus allowing large sheet heating elements to be implemented.

In summary, the PWM controlled heating element provides control over the power delivered to the heating element and thus provides us the ability to adjust the response time for achieving a target temperature, which would not be possible as mentioned before using a fixed voltage scheme.

4 Conclusions and Future Work

Intelligent prosthetic and robotic limbs are emerging. It is conceivable that the next technological step is to make these devices look and feel more humanlike in order to achieve more natural contact interactions with humans.

In this paper, the skin temperatures at the forearm, palm and the finger were obtained as these locations are possible areas where contact interactions could occur. The temperatures were obtained at different room temperatures. The suitable temperature range within which the human skin temperature gets regulated was found to be 21.3 to 36.5 °C. Flexible heating element was embedded on two different synthetic skin materials. The results show that it was possible to replicate the surface temperature of the human skin on these synthetic materials. Lastly, a power control scheme was developed for possible implementation of the heating system design to an actual prosthetic or robotic device.

From these preliminary results, a possible direction to undertake is to model the input power required for the heating element based on the room temperature and thermal properties of the skin material. The model can be used along with a modulation scheme to establish a controller based heating system that can automatically regulate the skin temperature of various parts of the prosthetic hand as an attempt to fully mimic the human skin temperature.

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Entrainment of Pointing Gestures by Robot Motion

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Abstract. Social robots need to recognize the objects indicated by people to work in real environments. This paper presents the entrainment of human pointing gestures during interaction with a robot and investigated what robot gestures are important for such entrainment. We conducted a Wizard-of-Oz experiment where a person and a robot referred to objects and evaluated the entrainment frequency. The frequency was lowest when the robot just used pointing gestures, and the frequency was highest when it used both gazing and pointing gestures. These result suggest that not only robot pointing gestures but also gazing gestures affect entrainment. We conclude that the entrainment of pointing gestures might improve a robot's ability to recognize them.

Keywords: Entrainment, Human-robot interaction, Recognition of gestures.

1 Introduction

Social robots are expected to provide services using objects in such real environments as transporting baggage or guiding [1]. To realize such services, robots must recognize the objects being referred to by people (Fig. 1).

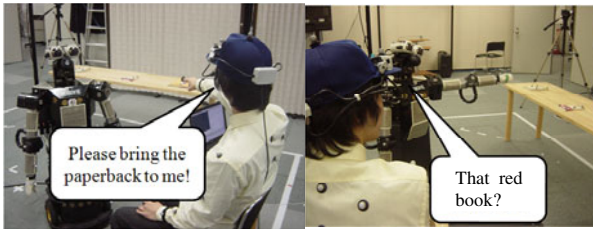


Fig. 1. Recognition of objects referred to by people

When referring to objects, people often use speech and gestures such as pointing behaviors. To improve the ability to recognize the indicated objects with speech and gestures, two approaches are available: an engineering approach and a cognitive psychological approach (Table 1). The former, which is very common in robotics,

recognizes speech and human gestures by interactions. The latter focuses on how people’s behavior changes during interaction with robots. If a robot can elicit understandable gestures and/or speech through human interaction, it can recognize them easily.

First, we explain the engineering approach to utterances. An important technology for this approach is voice recognition, which in robotics suffers from such acoustic problems as internal robot noise or background noise [2]. To address these problems, methods have been proposed that use multiple microphones [4] and sensors [3].

Next we consider the cognitive psychological approach to utterances. This approach has the potential to improve voice recognition functions. For example, if a voice recognition dictionary becomes too large, recognition efficiency and accuracy is worsened due to its huge search space. One method to solve this problem is lexical entrainment, a phenomenon that when people in conversation refer repeatedly to the same object, they come to use the same terms [5],[6]. In addition, lexical entrainment was reported to occur in situations where people and a robot referred to objects in real environments [7]. Therefore, lexical entrainment might interactively control the diversity of people's vocabularies and help reduce the size of voice recognition dictionaries, which would increase performance.

Third, the engineering approach to gestures includes recognition of people’s pointing gestures. A method for integrating eye directions and a speech interval was proposed to stably recognize pointing gestures [8], and a model of a relationship was also studied between pointing gestures and indicated objects to estimate pointing directions [9].

This paper focuses on the cognitive psychological approach to gestures; that is to say, a robot attempts to encourage people to make useful gestures for object recognition. Using an analogy from lexical entrainment, we consider the entrainment of the useful gestures. Although the entrainment of coordinated behaviors such as eye-contact or nodding has attracted attention [10]-[14], such useful gestures for recognition as directly pointing at objects have received little study. If a robot can interactively elicit such gestures from people as well as lexical entrainment, this entrainment could enhance the engineering approach to gestures.

Therefore, this paper studies the entrainment of human pointing gestures by clarifying the robot gestures elicited by pointing gestures through a Wizard-of-Oz experiment. Indeed the word "entrainment" in general means the synchronization of the biological rhythm between people during their communications, but we consider the word as the elicitation of a people's behavior by a robot. The focus of our work is not gestures with implicit meaning but the pointing gestures with explicit intention; therefore, we aim at inducing people's pointing gestures rather than synchronizing the rhythm.

Table 1. Approach to recognition of objects referred to by people

	<i>Engineering approach</i>	<i>Cognitive psychological approach</i>
Utterances	<i>Voice recognition</i>	<i>Lexical entrainment</i>
Gestures	<i>Gazing and pointing recognition</i>	<i>Focus of this research</i>

2 Related Works about Entrainment of Gestures

Entrainment of coordinated behaviors has been well studied in human-human and human-robot interaction.

Cognitive psychology in human-human interaction has shown that when two people converse, the listener's coordinated behaviors are entrained with the speaker's coordinated behaviors [15]-[19]. For example, Charny reported that the postures of patients and therapists are congruent in psychological therapy [18]. Condon et al. discovered that a baby's movements are encouraged by maternal speech [17]. Joint attention, the process by which people share attention to the same object though gazing and pointing gestures, can also be regarded as a kind of entrainment [19]. Thus many kinds of entrainment have been observed in interaction between humans.

Meanwhile, in human-robot interaction, the entrainment of coordinated behaviors has also been reported [10]-[14]. For example, Ogawa et al. developed a robot that was capable of synchronizing the nod of its head with human speech and observed entrainment of human nod motions through a conversation [13]. Ono et al. investigated human-robot communications involving giving and receiving route directions, and their results showed that people's gestures increased with robot gestures [12]. Such entrainments seemingly foster a sense of unity between a robot and people [14].

However, entrainments are less useful for improving the robot's recognition abilities. If the robot can elicit explicit gestures from humans to refer to objects, entrainment is beneficial for recognizing objects. This paper focuses on people's pointing gestures as one such explicit gesture and attempts to entrain the pointing gestures. We also investigate which robot gestures affect entrainment.

3 Experiment

We experimentally investigated the entrainment of people's pointing gestures using the Wizard-of-Oz method. This section describes the experimental task, procedure, environment, the role of operator, and the specifications of our robot.

3.1 Experimental Task

We developed a task in which people ordered a robot to move objects in an experimental environment. First, the robot asked people what object they wanted moved. After an object was chosen, the robot confirmed it with them. If the confirmation was correct, the subjects indicated another object; otherwise they indicated the same object again. Fig. 2 presents images of the experiment.



Fig. 2. Images of experiment

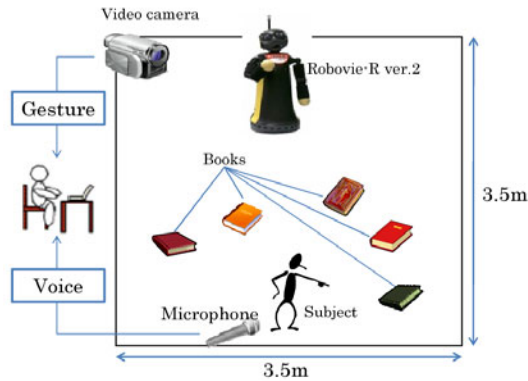
Table 2. Example of dialog

<i>Speaker</i>	<i>Dialog</i>
Robot	<i>Please indicate which book you want.</i>
Subject	<i>The travel magazine, please.</i>
Robot	<i>That one?</i>
Subject	<i>Yes.</i>
Robot	<i>Ok, please indicate the next one.</i>
Subject	<i>Hmm, carry this novel, please.</i>
	<i>(This task continues until all books have been indicated)</i>

The experiment employed books as objects because they are common household items. Moreover, they can be indicated by such expressions as titles, authors, colors, size, types, or contents. In other words, people don't need to point to refer to books. Table 2 shows a typical example of the conversation between subject and robot.

3.2 Environment

Figure 3 shows the experimental setup. We used a 3.5 by 3.5 m area in the center of a room due to the restricted area covered by the video camera. Subjects sat in front of the robot. Five different books were positioned between the subjects and the robot so that the subjects could identify them by sight.

**Fig. 3.** Experimental environment

3.3 Operator

This paper focuses on how to refer to objects in situations where people can speak and gesture freely. However, since current recognition technologies have difficulty precisely recognizing people's voices or pointing gestures, we cannot conduct the experiment smoothly. Therefore, an operator recognized the people's references by listening from a microphone attached to them and looked at their gestures from a video camera. The operator ran a behavior program for the robot corresponding to their voices and gestures. Considering the realistic recognition ability of future robots,

the operator rejected all references except the following three types: (i) bibliographical information, (ii) identifying attributions, and (iii) pointing.

For the first rule, bibliographical information includes a title, author, and category. The operator recognized a subject's indication by using not only the precise title but also a part of the title. For example, the travel magazine "Walking in Kyoto" was also recognized by speech "The book about Kyoto". This information is generally available to the public; therefore, we assumed the robot could obtain it.

The second rule is based on the supposition that a robot could choose a characteristic color or size by future image recognition techniques. However, we limited the recognizable words to those predefined by the experimenter.

The third rule was also based on the feasibility of pointing-gesture recognition. Even if subject's speech during the indication failed to satisfy the above conditions, the operator recognized an indicated book when he understood from the subject pointing gestures.

These rules allow the operator to make a consistent decision of the object recognition; therefore, even if a different operator is requested to do the experiment, the results are not considerably affected.

3.4 Humanoid Robot

Robovie-R ver.2 is a humanoid robot developed by ATR with a human-like upper body designed for communicating with humans (Fig. 4). It has a head, two arms, a body, and a wheeled-type mobile base. On its head, it has two CCD cameras for eyes and a speaker for a mouth that can output recorded sound files installed on the internal-control PC inside its body. The robot has the following degrees of freedom (DOFs): two for the wheels, three for its neck, and four for each arm.



Fig. 4. Robovie-R ver.2

3.5 Instructions

Subjects were told that we were developing a robot for object recognition and that we would like their help in evaluating the design. We also said that the robot could understand their speech and gestures and they could indicate as they prefer. All subjects received the same instructions.

Table 3. Speech in confirmation of indicated books

<i>Book</i>	<i>Speech in confirmation</i>
Book 1	<i>That one?</i>
Book 2	<i>That one?</i>
Book 3	<i>This one?</i>
Book 4	<i>That one?</i>
Book 5	<i>That one?</i>

3.6 Conditions on Confirmation Behaviors

To encourage entrainment of the people's pointing gestures, we focused on the robot's gestures used for confirmation, since confirmation is a typical process in human conversations. Confirmation is composed of speech and gestures.

Speech. The robot said deictic terms during confirmation (Table 3), because we needed to control the influence of its speech on people's pointing gestures. Its speech might cause lexical entrainment and change people's verbal expressions. According to the pre-experimental results, the frequency of their pointing gestures was affected by verbal expressions. Therefore, this paper standardized its speech in the confirmation of the deictic terms. Here, the deictic term for book 3 was "this" since it was the closest to both the subject and the robot.

Gestures. This paper attempts to discover a significant factor in gestures to encourage entrainment. Thus, we developed the following three conditions.

- *Condition G:* The robot uses only gazing gestures.
- *Condition P:* The robot uses only pointing gestures.
- *Condition GP:* The robot uses both gazing and pointing gestures.

In G, the robot turned its face and gaze on the indicated book for about 1 second, and its arms remained stationary in the side of its body at that time. Then, the robot said, "That one?" (See Table 3) and shifted its face and gaze to the subject, keeping its arm still. In P, the robot's face and gaze did not move and were directed on the subject, but only one of its arms moved to point at the indicated book. When the robot said, "That one?" its face, gaze and arms also still remained. The raised arm is put down after a response of the subject. In GP, the robot turned its face and gaze on the indicated book for about 1 second, and simultaneously put one of its arms up to point at the indicated book. After that, the robot said, "That one?", and then, it shifted its face and gaze to the subject, keeping the raised arm stationary. The raised arm is put down after a response of the subject.

3.7 Measurement

To evaluate the influence of different robot gestures on the entrainment of people's pointing gestures, we aimed at the following two kinds of measurements:

- *Gestures:* We captured people's gestures using a video camera and measured their pointing gestures in each condition.
- *Impression:* We asked subjects the three items shown in Table 4. They rated these items on 1-7 scale, where 7 is the most positive.

Table 4. Questionnaires

<i>Question #</i>	<i>Question</i>
Q. 1	<i>Could you easily instruct the robot?</i>
Q. 2	<i>Was the robot's confirmation easy to understand?</i>
Q. 3	<i>Was the conversation with the robot natural?</i>

3.8 Hypothesis

The following are our hypotheses. The frequency of the entrainment of people's pointing gestures will be changed by different robot gestures. We predict that the frequency will be highest in GP. In addition, impressions will also be better in GP than in other conditions.

4 Results

A total of 18 subjects participated in the experiment. All subjects were native-Japanese-speaking university students from Kansai area. The subjects were first given a brief description of the purpose and the procedure of the experiment. After this introduction, they were asked to review and sign a consent form. The experimental protocol was reviewed and approved by our institutional review board.

The subjects moved to the experimental laboratory to learn the details of the task. The subjects were assigned randomly to the three conditions. Since six subjects in each condition referred to five books, we obtained 90 references.

4.1 Gestures

The number of people's pointing gestures in each condition is shown in Fig. 5. The number was 69 in G, 39 in P, and 81 in GP. We compared these numbers using the

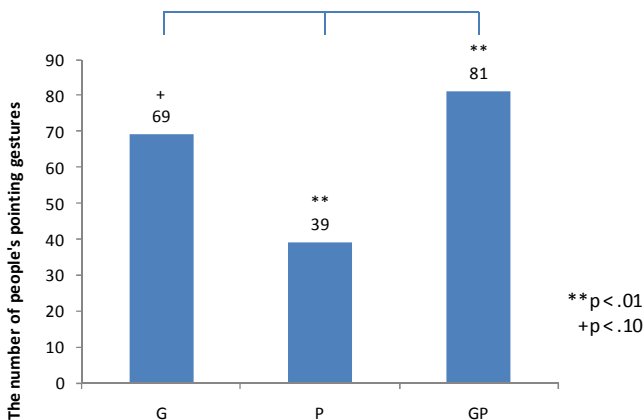


Fig. 5. Number of people's pointing gestures in each condition

chi-square test. As a result, the ratios of the numbers were significantly different ($\chi^2(2) = 49.524, p < .01$). Moreover, we did a residual analysis to determine the condition that included a significant difference. This result showed that the number in P was significantly low (adjusted residual = -6.761, $p < .01$) and the number in GP was significantly high (adjusted residual = 5.071, $p < .01$).

When the robot just pointed at objects without gazing gestures, people did not use their pointing gestures so much, but when the robot used gazing and pointing gestures, people frequently used pointing gestures.

4.2 Impression

Table 5 shows the means, standard deviations, and results of an ANOVA (analysis of variance) of the questionnaires. The ANOVA showed significant differences in Q. 3. The LSD method proved that the GP result outperformed the P result ($MSe = 1.3667, p < .05$). Confirmation that only included the pointing gestures looked more unnatural than confirmation that included both gazing and pointing gestures.

Table 5. Questionnaire results (where 7 is most positive)

Condition	Q. 1		Q. 2		Q. 3	
	Average	S.D	Average	S.D	Average	S.D
G	6.1667	0.6871	5.1667	1.675	5.1667	1.0672
P	6	1.1547	6	1.1547	3.8333	1.2134
GP	6.5	0.5	6.5	0.5	5.8333	0.8975
ANOVA results	F = 0.47(n.s.)		F = 1.55 (n.s.)		F = 4.55 (* $p < .05$)	
Multiple comparison						GP > G

5 Discussion

The results validate our hypothesis that the entrainment frequency of people’s pointing gestures is changed by robot gestures. The entrainment frequency was lowest in P and highest in GP. Here, even though the frequency in G did not show a significant difference, it was still higher than P. This suggests that the robot’s gaze is more important for the entrainment of people’s pointing gestures rather than just the robot’s pointing gestures. That is to say, even if the robot cannot move its arms such that it carries bags in both hands, the entrainment of people’s pointing gestures is encouraged by turning its gaze on indicated objects. Moreover, the suggestion is interesting because it may be applicable for social robots without arms, such as Papero [20].

Based on the questionnaires, people felt the conversations in GP to be more natural than the conversations in P. Since people usually look at objects when referring to them, even just a quick glance, this result seems appropriate. Moreover, Sato et al. reported that the performance of pointing perception was affected by gaze [21], which suggests that the gazing behavior of the robot not only makes unnatural conversation but also affects human perception. Such unnatural robot gestures might adversely affect entrainment. At least, in the context of eliciting the pointing gestures of people, the number of pointing gestures seems to correlate with the naturalness of an interaction from the results.

6 Conclusion

This paper reports which robot gestures were important to entrain people's pointing gestures, which is one approach to improve a robot's recognition ability of objects indicated by humans. We focused on the entrainment of human pointing gestures, which are essential for recognizing objects referred to by humans. We concentrated on gazing and pointing gestures of a robot to elicit human pointing gestures during interactions.

We conducted an experiment where a person and a robot referred to objects and developed three conditions about gestures: gazing only, pointing only, and gazing and pointing gestures. The number of human pointing gestures was lowest in the pointing only condition and highest in the both gestures condition. Questionnaires revealed that people felt the conversations in the pointing only condition were more unnatural than the both gestures condition. Our results suggest that the entrainment of people's pointing gestures is more affected by gazing gestures than pointing gestures and that entrainment is encouraged when natural communication is established.

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Emo-dramatic Robotic Stewards

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Abstract. In this paper will be presented an heterogeneous colony of robots capable to cooperate with people as effective partners to provide different kind of support among various working environments, such as museums, offices or trade fairs. Many systems have been integrated in order to develop robots capable to assists humans during the visit of the site, to guide them and to give information about the environment. According to the drama's theory, each robot has a different character, something like a personality, so, each of them will interact with people in a different way. Robots show also emotional, non trivial, behaviours using an LSA conceptual space capable to synthesize the different emotional states that each robot can express.

Keywords: HRI, robot colony, LSA, drama-tour, robotic guide.

1 Introduction

In recent years human-robot interaction studies captured the attention of researchers because the large variety of domains in which these studies could be applied. Latest results encourage the development of agents capable of learning, interact and working as a real, effective, partners with humans.

Different results from several research groups demonstrates many applications that can be conducted by robotic partners. W. Burgard, D. Fox and S. Thrun [19,7] used robots as tour guides in museum environments. H. Ishiguro [16,18] reported several robotics applications in wide, large-scale, daily life environments, such as train stations or museum. Furthermore, many studies [6,5] demonstrate that the robot capability to express emotions encourages a natural and believable interaction with humans, increasing the acceptance of the robot itself. Moreover, other researches [13,15] showed also that robots with a believable personality will be more accepted by humans, that become more disposed to interact closely with them.

This paper will present an easily scalable colony of robot stewards that can be used in museums, offices or receptions. These robots can offer assistance to

human users, or can be used to offer personalized tour guides. They can interact with people to provide aid, support and useful information. Recent studies [9] show that empathy makes the robot more accepted by the people, so the capability of arousing it in humans is important on the designing of robots that should collaborate with humans. In order to be accepted, robots needs to be perceived from humans not as objects but as “living creatures”, with a character, with past experiences and capable to express emotions. To achieve this, the drama theory [11] has been used to give to each robot a different personality. Each of them has a personal background, a psychological characterization, sympathies and antipathies, friends and antagonist. As in a theatrical drama or a film, each robot follows a plot and involves people in his personal story [2].

To improve its empathic capabilities, each robot is able also to express different emotional states through the communication modalities that it employs. Empaty and emotions grow up using a conceptual space built using LSA paradigm [10,8].

The study here presented focused also on different kind of robots: missions are chosen for each of them according to their hardware capabilities and to their phisical appearances, in order to enhance their performances.

Several experiments of the system have been performed in the Robotics Laboratory of Dipartimento di Ingegneria Informatica, University of Palermo.

2 System Overview

The proposed system is composed by several, different, robots that cooperates with humans in a real, complex and dynamic environment. The idea is to build a multipurpose mission system for colony of robots targeted to aid people during the exploration of an unstructured environment. Special attention has given to the empathic capabilities: each robot has its own dramatic characterization, and according to the drama theory follows a storyboard. Also, robots will interact with people in a natural way, expressing its own emotions that comes from this interaction. An assumption of this system is to be multiplatform: it supports different kind of robots with different hardware, controllers and HRI systems, so specific abstraction layers have been designed.

According to a modular approach, the system has been developed through the implementation of several computational units, each capable of solve specific problems. The different subsystem works together and exchanges information to accomplish the mission.

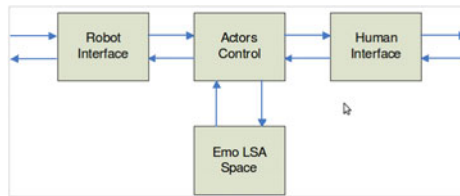


Fig. 1. A sketch of the system

The main module that coordinates all the actions of each robot is the “Actors Control” system. It chooses and executes the correct behaviour for the robot, using the high level information that come from the other modules, such as localization data, human presence, utterances from people, and the correspondent emotion that springs from them. The action selected is calculated using a script that each robot must follow, implemented as an FSA, and written according to the drama theory.

Two modules are designed to interface the “Actors Control” system with different robotic hardware. The “Robot Interface” implements the motion control algorithms, different for each platform, like localization, obstacle avoidance and navigation planning. The “Human Interface” system performs all the operation related to the interaction with humans, such as speech recognition, text to speech and face detection.

The “Emo LSA Space” system is used by the “Actors Control” system to generate emotions, according to the Latent Semantic Analysis paradigm: robots will change the prosody of the text to speech system, or will show particular, emotional poses, or will turn on some coloured led to communicate using a non verbal way.

3 Dramatic Characterization

According to the researches on dramatic characterization [17,12], the common elements of a drama are: the protagonist character that has a goal; the antagonist that opposes the protagonist’s attempt to reach his goal; the tension created by the obstacles that the protagonist encounters; the resolution of the conflicts at the end of the drama.

This schema is applied to the presented system in order to better involve users during the interaction and to improve the empathic characteristics of each robot. According to this schema, each robot plays a different role, has an unique past history, and follows a different script, so it will have a different point of view in the whole mission. Robots will “act” as character inside the drama. The goal is to make robots capable to be accepted by humans, so they should forget that robots are just machines: they must perceive robots as living creatures, with a personality.

As an example of drama theory applied to a colony of robots, it is possible to think about a story of robots that comes from the future or from another dimension: in this dramatic setup, while interacting with people to help them and to solve their problems, robots also involves humans in his story, by telling about it, about how they live in our world, and why they are not yet returned back to their home.

Robots chosen to be used in this project are very different: each of them arouse a different degree of empathy on humans and enhance their performances according to environments and missions. The designing of the drama must take in account all these characteristics.

4 Emotional Behaviours

To improve the empathic characterization of the robots, according to our past experiences [1], a system capable to infer emotions from the environment and the past experiences has been built. This system uses the Latent Semantic Analysis paradigm to create a conceptual space in which words and sentences are linked to emotions. Using this LSA-based system, the robot is able to find emotional analogies between the current status and the knowledge kept using the semantic space of emotional states. In this way the robot will be able to generate spontaneous and non trivial behaviours.

A large set of documents has been accurately chosen from internet. Each document is organized in homogeneous paragraphs each of which is associated to the feeling that emerges from it. In this way, a corpus of 1000 excerpt, equally distributed among the emotions has been composed. We decided to focus on the feelings of sadness, fear, anger, joy, surprise and love. Also a neutral state has been added.

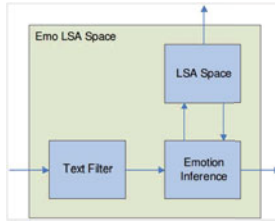


Fig. 2. The different modules used by the emotional system

According to the LSA theory a data-driven conceptual space has been created using this corpus, by linking the subset of words and sentences to specific behavioural categories, the emotions. Then, the environmental stimuli from the different perceptions are encoded and projected into the conceptual space and using a measure of semantic similarity with the different emotions, the system is capable to infer the feeling evoked by the current state. Robots will activate the most related behaviours to the inferred emotional state.

5 Actors Control

The behaviours of each robot are managed and directed using a distributed control system. Robots follow a plan in which are described all the actions that it can execute, according to the different situations. Each robot communicates with the others through a TCP/IP connection in order to synchronize behaviours with the other peers.

The idea to improve the humans empathy, according to the drama theory, is to design a drama plot in which each robot is an actor that plays a precise role,

with a characterization and a personal background. In order to create a system capable to be scaled to different roles and domains, this plot is expressed in terms of a finite state automata, coded in XML. Through this FSA it is possible to represent states and transitions among states: each state maintains the task that the robot has to execute in terms of simple behaviours; transitions are defined by some triggers that inform about the switching from the current state to another. Through this script it is possible to design in an easy way different characterizations. The script also helps the building of programs for the robot because programmers can “forget” the low level problems and can concentrate on building the plot of the drama.

6 Robotic Platforms

This project focus on different robotic platforms, humanoids and wheeleds, indoor and outdoor. Each of them has a various physical appearances and hardware, so capabilities and missions should be carefully chosen to obtain the best performances from each robot.

The robot Nao, from Aldebaran Robotics, is the humanoid platform chosen for this system. It carries on sensors to get information about the environment such as cameras and microphones. Aldebaran provides a framework capable to detect people, recognize speech and locate sound sources. It is possible also to use a set of coloured led in the body of the robot to communicate in a non verbal way.

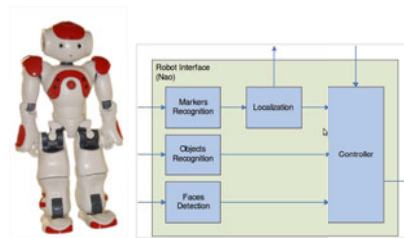


Fig. 3. The Aldebaran’s robot Nao and its control modules

Peoplebot and Pioneer P3-AT are the two wheeled robots from Mobile Robots focused by this system. They carries on lasers, sonars and a pan-tilt camera to acquire information from the environment. In particular, Peoplebot, tall with small wheels, is developed for indoor environments, while P3-AT, more stable and with big wheels, is designed for outdoor missions. Moreover, Peoplebot carries on a touch screen, so it can achieve a good degree of interaction with people, while P3-AT can use only the speech recognition and synthesis.

Peoplebot and P3-AT use the Player/Stage framework^[14] to simulate and control behaviours of the robots, so the same software can run in both the robots. Several Player subsystems have been used to move the robot in a safe way^[3,4], while a people detection system^[21,20] has been implemented.



Fig. 4. The Mobile Robot platforms Peoplebot and P3-AT Nao and their control modules, and the modules used by the human interface system

7 Experimental Results

Several experiments have been conducted in the laboratory of Dipartimento di Ingegneria Informatica of Università degli Studi di Palermo. Different robots have been tested and many situations have been achieved. Two experiments will be reported here. In the first experiments Nao, Peoplebot and Pioneer are used as receptionist to help people in the department to find professors. In a second experiment, the robots are used as museum guide, to conduct people among several exhibits.

7.1 Receptionist Robot

In this experiment different robots, operates to bring people from the department doors to the professors rooms. Robots used were Nao, Peoplebot and Pioneer. According to the hardware differences, each robot played a role that emphasize its performances. The humanoid Nao has been used as doorman because its high interaction capabilities.

Nao stays on a table near the entrance door of the department, waiting people. The robot prevent falling down from the table using a vision based localization system: some markers are applied near the borders of the table in order to make it able to stay away from them.

People that approaches the robot is detected through the face detection system: after some greetings the robot asks about the professor to reach. Then, the first free robot between Peoplebot and Pioneer is called and, when it is near, human is invited to follow it.

While following the robot, human is encouraged to interact with it. A story has been designed for this robot colony according to the drama theory. Robots think that the department is their home and they will talk about the experiments carried on by “their brothers”, the robots and the computers that are in the laboratory. Robots stay away from areas of the department in which the wireless signal is too weak, saying that they “fear those places”. In this story there is also an antagonist, the cleaning woman: her mission of cleaning everything puts the robots on alert, and they do everything to avoid encountering her!

The robot keeps in memory a map of the department, previously created. Through this, they are able to safely plan and follow a path to several position

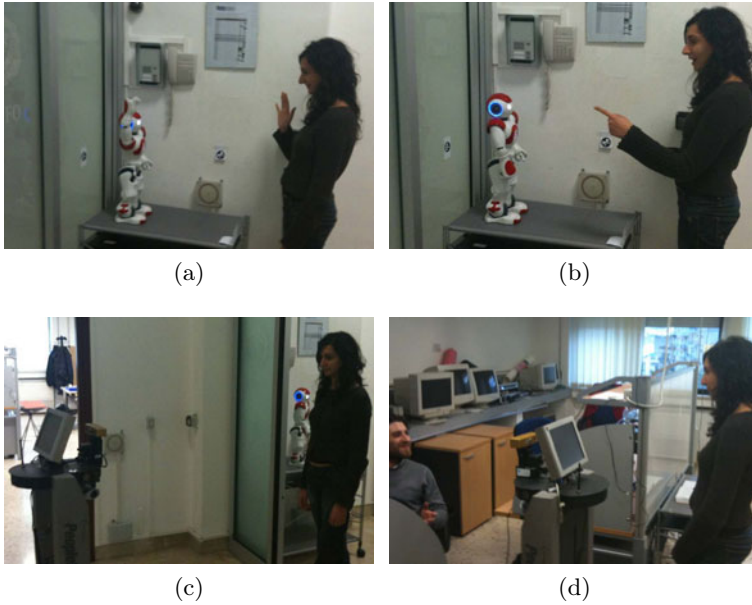


Fig. 5. Nao welcomes the human user that asks for a person, then human user follows the Peoplebot to the goal

related to the door of the each professor room. Robots also move safely through dynamic obstacles, such as people that moves inside the department, and avoids them. When the robot brought the human user to the professor, it returns back to its initial position in front of the department door, waiting new people from the Nao doorman.

7.2 Museum Guide

In a second experiment, the system has been adapted to work inside a museum: in this case robots plays as tour guides. The system has been tested inside the laboratories of Dipartimento di Ingegneria Informatica of Università degli Studi di Palermo, by creating a kind of museum of IT history, using some old informatics stuffs as pieces of exhibition. The environment is composed by two long corrido4rs, each of which has been provided of some stands with the pieces. These kind of passageways has been used as two separates competency area for the wheeled robots: the firts one area is assigned to the Peoplebot, whereas the second one is competency of the P3-AT.

One of the two Nao has been used as a receptionist, to welcome the people that waits to beginning of the tour. When the Peoplebot, used as first guide is free, the Nao invites the group of person to follow it and the tour starts. The wheeled robot guide the persons inside its competency area and stops in front of each piece of the exhibit to explain something about it. People is encouraged

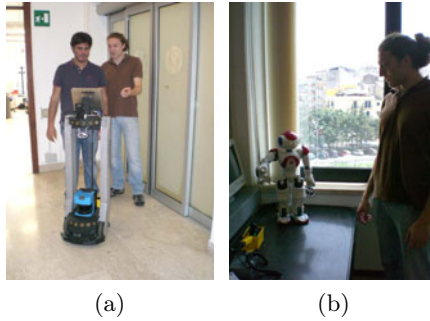


Fig. 6. Tour guides are offered by Peoplebot and by Nao

to interact with the robot through the human interface of the robot itself. A second Nao is placed beside an important piece: when the wheeled robot stops in front of it a synchronized signal is sent to Nao that starts its explanation and acts as an “expert”, more capable to interact and reply to the people about the “masterpiece” that is showed.

When the Peoplebot completes his guide, the wheeled robot brings the group in a previously chosen rendezvous place to meet the P3-AT: when this last robot will be free, it will take the leading of the group and it will bring them through the second part of exhibitions, its competency area. In this experiment P3-AT has been used also in an indoor environment, but its capabilities are emphasized in outdoors environments. At the end it will bring people to the exit.

7.3 Discussion

Robots used in this project have a very different hardware. The mission in which each robot will be involved should be chosen according, first of all, to its physical architecture: fast wheeled robots are used to operate in large environment; small humanoids can safely move in little areas, and should be employed for strictly interaction with people. However, the physical appearance of the robots modify the perception that humans have of its behaviours: in particular, the humanoid robot Nao is capable to generate a big empathy because its shape is cute, it resemble to a child, and it is easy to anthropomorphise it. Pioneer and P3-AT, on the opposite side, generate a weak empathy. Despite of this, experiments seems to show that the artificial intelligence, the drama paradigm and an emotive appearance will help to improve the empathic performances: the closeness between robotic beings and human beings result reinforced by presenting intelligent behaviours and by showing a strong characterization.

8 Conclusions and Future Works

A colony of robot stewards capable to help people in different situation has been developed. The design process took in account several constraints: the system

can be implemented in different platform and it is flexible to be adapted to many situations. Improving empathy in the human users has been one of the main targets of this system. On one side, using the approach of the drama theory, a storyboard has been designed and, on it, several characterizations, one for each robots, have been designed: each robot is an actor of the drama. On the other side, each robot is capable to “feel” emotions that grow up from the interaction with people and from environmental stimulus, using an emotional LSA-based conceptual space. The experiment, here exposed, encourages us to pursuit this kind of researches: the systems accomplished different missions in different environment. The dramatic characterization seems to improve the empathic performances of the robots: people “feel” the robot and consider himself as involved in the story. Also, using the emotions, it becomes possible the generation of spontaneous and not repetitive behaviours.

As future works, the system will be employed in a real daily-life environment, such as the Botanical Garden of Palermo and the Archaeological Museum of Agrigento. In these environment, with non expert, and naïve users, it will be possible to collect statistics about the effectiveness of the empathic interaction. It will be also collected data in order to understand the efficacy of the use of robots in different missions and in different environments.

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Fusion and Self-adaptation of Color and Gradient Based Models for Object Detection and Localization in Applications of Service Robots

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Abstract. This paper presents a novel approach of object detection and localization for service robots, which combines color-based and gradient-based detectors and automatically adapts the color model according to the variation of lighting conditions. Exploiting complementary visual features, the fusion of color-based and gradient-based detectors can achieve both robust detection and accurate localization. In real world environment, the color-based detection according to an offline-learned general model may fail. From a new linear color variation model proposed in this paper, our approach can generate a specific model for the target object in the image and achieve self-adaptation of color detector for robust detection and accurate localization. The experiments show that the proposed method can significantly increase the detection rate for target object in various real world environments.

Keywords: Service Robot, Object Detection, Object Localization, Color Segmentation, Self-Adaptation, Fusion.

1 Introduction

Object detection and localization is one of the key functions for service robots to serve people in houses, offices, and healthcare centers. For example, one task of FusionBot [8] is to serve coffee to the requester in a house. In this scenario, robot needs to detect and localize the cup and coffee machine. Robot may be required to provide service in different places in very different lightings. Hence, one of most significant challenges for real world applications is the accuracy and the robustness of object detection and localization under varying lightings.

In the past two decades, the great progress has been achieved in object detection from images [1-12]. Existing methods can be classified into two categories: bottom-up and top-down approaches. In bottom-up procedure, each pixel in the input image is first classified into either the object or non-object pixel according to local feature, e.g. color, texture, or motion [2-5]. The labeled object pixels are then connected into regions. The extracted region is confirmed as a target object by the shape similarity measure [5]. The bottom-up approaches are efficient and can produce an explicit object segmentation, which is needed for robot to grab the object. However, they are easy to fail due to big illumination change since the local feature, mainly being the color

distribution, is sensitive to lighting condition. A set of sparse feature points, e.g. SIFT [9], can also be used for bottom-up detection, but it has no explicit segmentation. For top-down approaches, a global model of the target object, e.g. the histogram of gradient orientation (HOG) [1], is generated from a large training dataset by a support vector machine (SVM) or Adaboost. In detection, multi-scale detection windows are used to scan the whole image. At each detection window, the global model is applied. The target object is detected if the response from the window is positive. The advantage of the top-down approaches is the robustness to lighting conditions and complex backgrounds due to the global gradient feature representations, but they do not explicitly segment the detected object. The computational cost is also very high due to the multi-scale scanning. Various color models have been proposed and well-studied for object detection, e.g., the color spaces and color distribution models [2-5]. Existing researches focus on finding an illumination invariant color model [5]. The invariant color model might be either too general for a target object in a specific scene or too sensitive to lighting change. Zhou *et al* have proposed to use the shape constraint to update color models [12]. Its performance depends on a good initialization of shape recognition which might not be available when the color-based detection is poor.

This research targets to develop a robust object detection and localization approach for service robot in house, office, healthcare center, and museum. We propose a framework to combine the color-based and HOG-based detectors. The HOG-based detector is robust to lighting conditions, but it may produce many false-alarms on complex backgrounds. The color-based detector is sensitive to lighting conditions. However, the obtained segmentation provides an accurate position of the object, and moreover, the color model can be used to suppress false detections by HOG detector and identify the correct target object if multiple objects of the same class with different colors in the scene, e.g., identify the red cup when several cups of different colors on the table. In color model, we propose a *linear color variation model* which reflects color model change with lightings. It can not only generate a more accurate color model for the object in a specific scene but also provide the color model for the object in an unknown lighting condition. Fused with HOG-based detection, the proposed method can perform self-adaptive object detection, which can significantly improve the accuracy and robustness of object detection and localization.

The rest of the paper is organized as follows. Section 2 gives an overview of the general architecture of our framework. Section 3 and 4 describe the bottom-up color-based detector and top-down HOG-based detector respectively. Section 5 and 6 present the fusion and self-adaptation for robust object detection and localization. Section 7 presents the experimental results. We conclude the paper in Section 8.

2 General Architecture

The framework of our approach is depicted in Fig 1. First, color- and HOG-based detections are performed separately, where sparse scanning of the image with coarse scale levels and large spatial shifts are used. The results are then fused with 3 tentative scores: accept, reject, and uncertain. Each uncertain case is considered as a hypothesis for the second round detection. The self-adaptive round detection is performed in two cases. Case 1: HOG detection with no support from color-based

detection. In this case, we estimate the specific color model from the possible position indicated by the HOG detector and perform color-based detection using the specific color model. Case 2: color-based detection with no support from HOG detector. In this case, we perform refined HOG-based detection around the position with restricted scale and small spatial shift. For the true hypothesis, the fusion of self-adaptive detections (second round) will result in an output of “*accept*”, otherwise, the hypothesis will be rejected. In Fig 1, the black and the blue arrows indicate the flow of the first and the second round detections respectively.

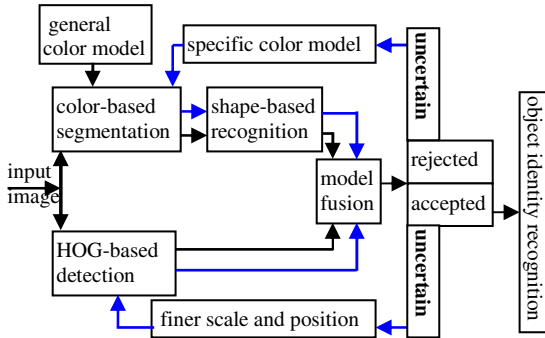


Fig. 1. Block diagram of our framework of fusion and self-adaption of color and gradient methods

3 Bottom-Up Object Detection

3.1 Color-Based Object Segmentation

Here we use Gaussian distribution for object color.

Gaussian Color Model: For a target object, the Gaussian model $N(\mu, \Sigma)$ in RGB space is used, where μ and Σ are the mean vector and covariance matrix given in equation (1).

$$\mu^T = \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{and} \quad \Sigma = \begin{bmatrix} \sigma_{RR} & \sigma_{RG} & \sigma_{RB} \\ \sigma_{GR} & \sigma_{GG} & \sigma_{GB} \\ \sigma_{BR} & \sigma_{BG} & \sigma_{BB} \end{bmatrix} \tag{1}$$

This model is obtained from sample pixels. The general color model (μ_m, Σ_m) of the target object is obtained offline from manually collected samples under various lighting conditions, while a specific color model (μ_t, Σ_t) of the target object is obtained from the pixels of the object in a specific image I_t .

Color-based Segmentation: For a color vector \mathbf{c}_x from a pixel x , the probability of \mathbf{c}_x belonging to the object is calculated as

$$P(\mathbf{c}_x) \propto |\Sigma_m|^{-\frac{1}{2}} e^{-\frac{1}{2}(\mathbf{c}_x - \mu_m)^T \Sigma_m^{-1} (\mathbf{c}_x - \mu_m)} \tag{2}$$

The pixel x is classified as one potential object pixel if its probability value is larger than a threshold. The potential pixels are connected into isolated regions.

3.2 Object Shape Recognition

The shape descriptor presented in our previous paper [7] is used here. This descriptor defines on a set of normalized second-order moments. The moments of the silhouette are calculated as follows. Let $R(x,y)$ be the binary region of object. The gravity centre of the segmented region is computed as

$$x_c = \frac{m_{01}}{m_{00}}, y_c = \frac{m_{10}}{m_{00}} \text{ and } m_{ij} = \sum_{(x,y) \in I_{p-obj}} x^i y^j R(x,y) \tag{3}$$

where I_{p-obj} is the image of the potential object within the bounding box of the segmented region. The set of central moments are then computed as

$$\mu_{ij} = \sum_{(x,y) \in I_{p-obj}} (x-x_c)^i (y-y_c)^j R(x,y) \tag{4}$$

The normalized second-order central moments is defined as

$$\phi_1 = \sqrt{|\mu_{11}|} / m_{00}, \phi_2 = \sqrt{\mu_{20}} / m_{00}, \phi_3 = \sqrt{\mu_{02}} / m_{00} \tag{5}$$

The normalization of the moments makes the shape feature scale-invariant. The feature vector $\mathbf{v} = (\phi_1, \phi_2, \phi_3)^T$ forms the shape feature vector. The shape model of a target object is learned from manually collected samples. The trained object model is then represented by the average feature vector $\bar{\mathbf{v}}$ and the covariance matrix Σ . For the silhouette classification, given an input feature vector \mathbf{v} , the likelihood probability of the input feature vector to be the object, which is used to identify object pixels, is computed as

$$P_{obj}(\mathbf{v}) = (2\pi)^{-\frac{3}{2}} |\Sigma|^{-\frac{1}{2}} e^{-\frac{1}{2}(\mathbf{v}-\bar{\mathbf{v}})^T \Sigma^{-1}(\mathbf{v}-\bar{\mathbf{v}})} \tag{6}$$

4 Top-Down Object Detection

Here we use the Histogram of Oriented Gradient (HOG) [1] detector for top-down object detection. The detection window is divided into $K \times L$ cells. The window covers the object with a margin of a cell size all around. In a detection window, each group of 2×2 cells forms a block. The blocks overlap each other in a sliding way, so a detection window of $K \times L$ cells forms $(K-1) \times (L-1)$ blocks. The local texture feature in each cell is represented by a HOG where the orientations of gradients from -90 to 90 degree are quantified into 9 bins. Thus, each block is represented by a concatenated 36-bin histogram from all of its cells. The histogram of each block is normalized using $L2$ -norm scheme. Then, the histograms of the blocks are concatenated to form the HOG vector of $(K-1) \times (L-1) \times 36$ elements for a detection window. A SVM classifier is trained using the HOG vectors from a large sample set comprising both positive and negative instances of objects. The trained HOG detector is then used to

detect object from input images. To be efficient for real-time task, we scan the image with fewer scales of detection windows on sparse positions in the first round.

5 Fusion of Bottom-Up and Top-Down

We fuse the bottom-up and top-down detections to utilize the robustness of HOG-based detector and the accuracy of color-based detector in localization and identification. A bounding box (B_c) can be generated from the segmented region by color-based detection, while a box (B_e) can be obtained from each HOG-based detection. The HOG-based detection may generate a cluster of boxes for a target object. The agreement of two detections can be evaluated as the overlapping of the boxes, i.e. $m = |B_c \cap B_e| / |B_c \cup B_e|$. Then, the tentative score of the detection by fusion can be given as

$$S = \begin{cases} 2 & \text{if both color/shape and HOG detect the object,} \\ 1 & \text{if either color/shape or HOG detects the object,} \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

The object is confirmed if S is 2; no object is confirmed if S is 0, otherwise the self-adaptive detection according to the feedback is conducted. If the score is increased, the detection will be accepted, otherwise it is rejected. In this way, we can achieve high efficiency for real-time system and strong robustness for real-world environments.

6 Self-adaptation Object Detection

If either the bottom-up or top-down detections fails, it means that there might be an object with ambiguity due to unknown lighting, complex background, or unmatched scale of position. We then perform the self-adaptive detection to verify the hypothesis. We work on the two cases. 1) HOG detection succeeds but the color-based detection fails; and 2) the color-based detection succeeds but HOG-based detection fails.

6.1 Case 1: Self-adaptation Color-Based Detection

In this case, we generate a specific model for the region detected by HOG for self-adaptive detection.

Color Variance Model: Under different lightings, the distribution of the distinctive colors of the target object is different. The local average of the colors provides an important clue for the lighting condition. Hence, a novel linear model is proposed to estimate the color variation under different lighting conditions. For a target object, suppose $\bar{C}_i = (\bar{R}_i, \bar{G}_i, \bar{B}_i)$ is the average RGB vector of the potential region in the input image I_i . The variance of the colors in this specific scene (or image) should be derived from the general model and the corresponding lighting strength for this scene. Since the covariance matrix is always a positive-definite matrix, the color variance model can be defined as

$$\Sigma_t = Q_t^T \Sigma_m Q_t \quad \text{with} \quad Q_t = \mathbf{F}(\bar{\mathbf{C}}_t) \tag{8}$$

Where Q_t is the mapping matrix to estimate the color variance of the target object in the specific scene and it is obtained by the color variance model $\mathbf{F}(\cdot)$. Q_t should be a positive-definite matrix, hence, it can be defined as

$$Q_t = \text{diag}(s_R^t, s_G^t, s_B^t) \tag{9}$$

with $s_p^t > 0$ for $P = R, G,$ or B .

From (8), we have $\sigma_{PP}^t = (s_p^t)^2 \sigma_{PP}^m$ and the linear model to predict the specific color model can be defined as

$$\sqrt{\sigma_{PP}^t / \sigma_{PP}^m} = \tilde{\sigma}_{PP}^t = s_p^t = k_p \bar{P}_i + b_p \tag{10}$$

where k_p and b_p for $P=R, G,$ or B are the parameters of the linear model $\mathbf{F}(\cdot)$.

The color variance model (10) or (12) can be learned offline from N training samples captured from different lighting conditions. From each training sample, we can obtain $\{\sigma_{PP}^i\}$ and $\bar{\mathbf{C}}_i = (\bar{R}_i, \bar{G}_i, \bar{B}_i)$. Let

$$\mathbf{y}_p = (\tilde{\sigma}_{PP}^1, \dots, \tilde{\sigma}_{PP}^N)^T, \mathbf{X}_p^T = \begin{pmatrix} \bar{P} & \dots & \bar{P}_N \\ 1 & \dots & 1 \end{pmatrix}, \mathbf{a}_p = \begin{pmatrix} k_p \\ b_p \end{pmatrix} \tag{11}$$

Using least-square estimation, the parameters for the color variance model in equation (10) can be obtained as

$$\hat{\mathbf{a}}_p = (\mathbf{X}_p^T \mathbf{X}_p)^{-1} \mathbf{X}_p^T \mathbf{y}_p \tag{12}$$

Self-adaptation Color-based Detection Procedure: In case 1, we can obtain a bounding box of hypothesis (B_e) from HOG-based detection. From the central core region of B_e , we can obtain the average RGB vector $\bar{\mathbf{C}}_i$. Then, from (10), we can estimate the covariance matrix. This estimated specific color model for the object in this image is used in self-adaptive detection using in equation (2).

6.2 Case 2: Self-adaptation HOG-Based Detection

In this case, from the segmented region by color-based detection, we can predict the center position and the scale of the hypothesis. Then we apply the HOG detectors of the scales from 0.8 to 1.2 times of the estimated scale on the positions around the estimated center. If the HOG-based detection success in these refined detections, the hypothesis is verified, otherwise, it is rejected.

7 Experimental Results

To evaluate the performance and benefits of our proposed method for real applications, the experiments are conducted and the quantitative evaluations are performed. The task of our algorithm is to detect and localize a target cup for guiding robot to



Fig. 2. A success example of detecting the white cup in a complex environment with many similar color objects, e.g., shadows, reflections, walls, and furniture



Fig. 3. A success example of detecting yellow cups in a room with similar colors from wall, door, and book shelf

grab it. This task is required for a robot to serve drinks in home, office, healthcare center, and public event. Several sequences are recorded for each cup in different environments under various lightings (indoor and outdoor). We will show some examples and present the statistics of the results below.

Table 1. Evaluations on the algorithm for object detection on the two test datasets

white cup	#frm	HOG	Color	Fusion	Adapt.
	120	161	87	71	95
	Recall	100%	59.2%	59.2%	79.2%
yellow cup	#frm	HOG	Color	Fusion	Adapt.
	181	739	118	109	154
	Recall	97.8%	65.2%	60.2%	85.1%
	Accuracy	24.0%	92.4%	98.2%	100%

The first test evaluates the performance of applying our method on a white cup with various lighting conditions. The test data set contains four sequences captured under the different lighting conditions, e.g., different outdoor and indoor lightings under various weathers. Even in each sequence, the colors of the white cups vary greatly when observed from different distances and view angles. We randomly select 30 training samples from 2 sequences, and then test on all the sequences. One example of this test is shown in Fig. 3, where the first image (*from left to right*) shows HOG-based detections, the second image shows color-based segmentation in the first round using the general color model, the third image shows the result of self-adaptive color-based segmentation in the second round using the online generated specific color model, and the last image shows the final detection result indicated by the red bounding box. The target object for the second test is a yellow cup, a typical solid

colored object. Again, we capture four test sequences under different indoor or outdoor lighting conditions and varying view angles and distances. First, we randomly select 123 samples to train a general color model. Then, we randomly select 181 test images from the rest of the frames to form a test data set. One example of this test is shown in Fig. 3, where the images are laid out as in Fig. 2. From these 2 examples, one can find that the HOG-based detector may generate many false detections on the background and a cluster of detections on true objects, color-based detection can help to identify the correct target. However, the general color model covering the color distributions of target object under various lighting conditions may not accurate enough for a specific scene, which would result in over-segmentation in bottom-up detection due to too many background pixels are misclassified as object pixels. Using the online generated specific color model predicted by the linear color variance model, the target object can be successfully detected in the second round self-adaptive object detection. The statistics of the quantitative evaluations on two test datasets are summarized in Table 1. It can be seen that, in average, more than **20%** of the increase on detection rate has been achieved by self-adaptive detection.

8 Conclusions and Future Work

This paper presents a novel approach of object detection and localization for service robots in real-world applications. The fusion of top-down HOG-based and bottom-up color-based detectors is used to recognize object. However, the HOG-based detector may generate many false detections and the color-based detector is sensitive to lighting conditions. Self-adaptation for object detection in difficult scenarios is further proposed. To achieve this, a linear color variance model is proposed and used to generate a specific color model online for self-adaptive detection. Experimental results and systematic evaluations have shown a significant improvement in object detection in real world conditions.

In the future, we will apply the proposed method to recognize not only solid colored objects but also objects with rich texture features and visual patterns.

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Development of Robotic Arm Rehabilitation Machine with Biofeedback That Addresses the Question on Filipino Elderly Patient Motivation

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Abstract. Many robotic systems have been developed for assisting rehabilitating stroke patients. Their failure lies on the system design's inability to motivate the patients to voluntarily conduct different activities that could stretch the impaired arm to its limit and help improve its condition. This paper presents the development of a robotic arm which allows the stroke patients' active involvement in their rehabilitation through real-time biofeedback. It also evaluates the condition of the patients based on their performance and sends this feedback so therapists or doctors can monitor patients' improvements. This project espoused a recommended strategy on patient motivation, that is, to embed therapy within the framework that provides patients with monitoring and interaction with therapists. Initiated for the needs of Filipino stroke patients, this paper presents its acceptability in the light of Filipino values.

1 Introduction

The growing need for neurophysiological therapy and physiotherapy has given rise to researches on robot-mediated therapy systems. The robotic arm rehabilitation machine with biofeedback system was developed to address the need for rehabilitating stroke patients. Intended primarily for the Filipino clientele, the machine developed was low-cost and effective in its intended function.

The purpose of the machine was to rehabilitate the arm of the patient in order to support lateral forearm movement. After rehabilitation, stroke patients would be able to do daily tasks such as feeding oneself, buttoning one's shirt, brushing one's teeth. The machine performs active motion therapy by augmenting the motion of patient's arm while a biofeedback system helps the patient gain conscious control of arm movement.

Much has been written about the importance of patient motivation in recovery of stroke patients. Such participation and involvement of the patient, researchers said, have led to their early recovery in the use of their limbs. Incorporating a biofeedback system to the robotic arm rehabilitation machine was a decision undertaken by the

machine developers in order to involve the patient in his therapy. It is intended that he will not merely be a recipient of therapy but will participate actively in the process, given the simple decisions to stretch the weak limb beyond the perceived limit noted in the reading. Discussions regarding the biofeedback system and patient motivation are presented in the next section.

1.1 Literature Review

Biofeedback is the process of identifying physiological variables such as muscle activity, peripheral skin temperature, regional blood flow, respiratory style and rate, heart rate variability, brainwaves and other measures of autonomic nervous system function for the purpose of helping the patient to develop a greater sensory awareness [1]. Electronic instrumentations, such as Surface Electromyography, Skin Temperature, and Heart Rate Variability, are used to monitor these physiological variables. These instruments give visual or audio feedback for the purpose of teaching the individual to gain some measure of physiological control.

Biofeedback is a treatment technique in which people are trained to improve their health by using quantifiable functions or signals from their own bodies, then conveying the information to the patient in real time which thus raises the patient's awareness and conscious control of their unconscious physiological activities. Reviews on biofeedback in rehabilitation show therapeutic and clinical applications [2, 3, 4]. Biofeedback provides functional and task-oriented trainings to improve motor control among stroke patients. Training includes visual, auditory and physical interactions which offer real-life experiences to stroke patients. Results show that trainings lead to improvements in voluntary control, motor coordination, and range of motion.

The study of Huang *et al.* [5] has utilized biofeedback as an interactive and task-oriented tool to promote motor learning in two patients with hemi-pareses due to stroke. In this case, when presented with visual and auditory feedback, the patients were able to perform smoother movements. Such results suggest that sensory overloading need not be a concern with the provision of a well organized multimodal augmented feedback of the design.

The rehabilitation training that a stroke patient undergoes is effective when it reduces functional disability and when it induces him to carry over his exercises and therapy gains in his daily living environment [6]. Recovery could be enhanced if the patient transfers the skills they have gained from supervised training into their living environment even without regular supervision from their therapist [7, 8]. One obstacle to recovery is the learned non-use of the affected limbs. A patient who has been familiar with setting aside the use of the affected limb in favor of other possible ways to serve his intents would find it difficult to reverse and get used to depending on his affected limbs. In due consideration of this, the training exercises have to be preferred acts or movements of the patient; they should be repetitive and controlled by the patient.

One factor that would have to be incorporated in robot-assisted therapy systems is patient motivation. This is provided by incorporating strategies that are client-centered, task-specific training that emphasizes the use of the arm in diverse, real tasks, and uses other incentives to encourage and sustain arm use inside and outside of training. Strategies were presented that were designed to motivate as well as to rehabilitate patients [6]. These are to 1) embed therapy within a framework that provides

patients with monitoring and interaction with therapists, 2) embed therapy into fun, video game-like activities, and 3) embed therapy within patient-centered real-life functional activities. These are usually incorporated in the biofeedback system.

The robotic arm that is an outcome of this project is a combination of strategies 1) and 2). In this project, therapy is embedded into fun, video game-like activities while providing the patients with self-monitoring and possibility of easy assessment by the therapist.

1.2 Product Design Features

The most important feature of this project is the software programming that incorporates a game and biofeedback to the rehabilitation process. The game is controlled by the patient via the rotating arm bar, and will encourage the patient to go about his rehabilitation procedure. Through the objective based nature of the game patients have visible goals such as higher scores developing motivation. The software's input will mainly be the position of the arm using data attained from the encoder. The output of the software will mainly be of two things: biofeedback (the game) and a generated report.

The visual and audio feedback is developed using Microsoft Visual Basic 6. In addition to that, Microsoft Access is used for database storage which keeps all the information and data of the activities done by the patient. The software generates a report in a Microsoft Excel file.

The software key features are the practice, game, and the reporting system. Biofeedback is incorporated in practice and game modes where in the patient could see the motion of his arm in a visual form. Added to that, sound was also included to add to the patient's interest during the therapy.

2 Software Design

2.1 Practice

The practice involves the active and passive motion. A sample screenshot is shown in Figure 1. In this activity, the motor can be set to: active/passive and passive setting.

In the active/passive setting, the patient attempts to move towards the target (red circle) following a predetermined trajectory. If the patient could not make it, the machine will assist his arm to complete the motion. The green circle indicates the position of the patient's arm. The number of targets hit with and without assistance of the machine is also shown in the screen. Take note, physically motion is not limited to 180° however motions extending beyond this range will simply register as the red bar reaching its maximum position in that direction.

In the passive setting, the patient relaxes his arm while the machine passively moves and assists his arm from starting point towards the target.

2.2 Game

During the game, the patient has the full control in moving his arm attempting to deflect the ball using the rectangular "Pad" from touching the bottom of the screen, whenever ball is successfully deflected a "boing" sound will occur and another when

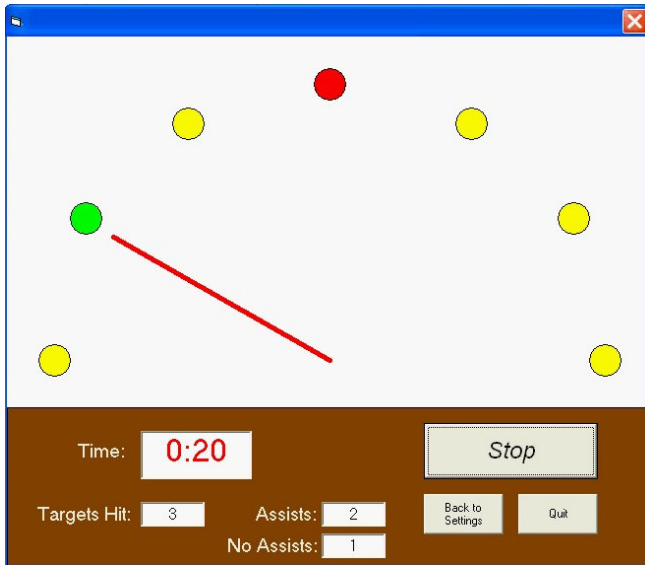


Fig. 1. Practice

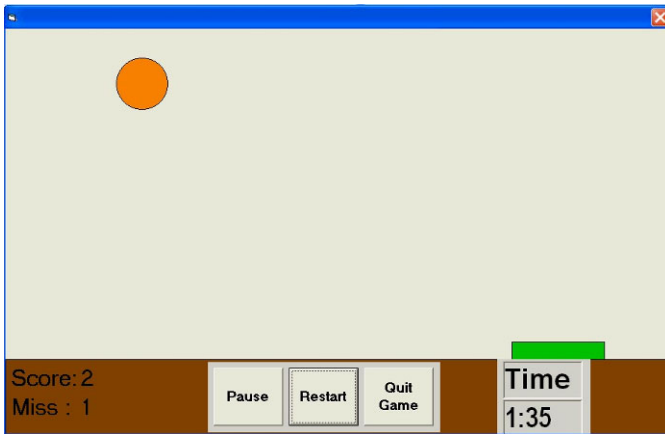


Fig. 2. Game

otherwise. Patient's dexterity is evaluated in this activity. The number of times the patient catches and misses the ball is recorded during the activity as shown in Figure 2.

2.3 Reporting System

A database, which holds all the patients' information, is incorporated in the software. It also records all the activities done the by patients. At the end of each activity, all the encoded information, settings used, and results of the activity are recorded in the

database. With this, the software can generate report at the end of each practice or game activity.

Sample reports are shown below. Basically, the reports show results of the activity done and other details encoded by the doctor or therapist. In the practice report, important details such as the following are shown:

- Arm in Use
- Motor Setting
- Speed, Duration, Number of Repetitions
- Number of Times that Target was Hit with Assistance
- Number of Times the Target was Hit without Assistance, and
- Numerical Assessment

While in the game, the report shows the score, miss and assessment. For both, the details included in the report are very important for the doctor's assessment.

The software has the capability to generate a history report which shows the activities done by the patient. This includes all the information recorded during practice and game therapy session. The history report enables the doctor to evaluate patient's improvement by comparing the data of the different activities done by the patient throughout the rehabilitation process.

2.4 Safety Considerations

First, a panic button is placed within the patient's reach so that he could immediately stop the machine if he feels pain during the therapy. Figure 3 shows the location of the button in the machine.

A sensor is also used to constantly measure the body temperature of the patient preferably in the biceps, wrist or underneath the armpit of the arm being rehabilitated. It will help ensure that the patient's body temperature remains below the safety mark to keep the patient in a comfortable state. If the patient reached a temperature of 37.5 °C, the machine will automatically stop preventing any discomfort that it may cause to the patient.



Fig. 3. Panic Button

In the conceptualization and development of the robotic arm here presented, the inventors also considered the psyche of the Filipino. The intent is to make it acceptable to the Filipino stroke patients as well as elderly stroke patients and their family members.

2.5 The Filipino Psyche

Based on studies [9] it was stated that characteristics of the Filipino and the values he has inherited from the Chinese, Malays, Spaniards and Americans, the Filipino has the hierarchy of needs as shown in Figure 4.

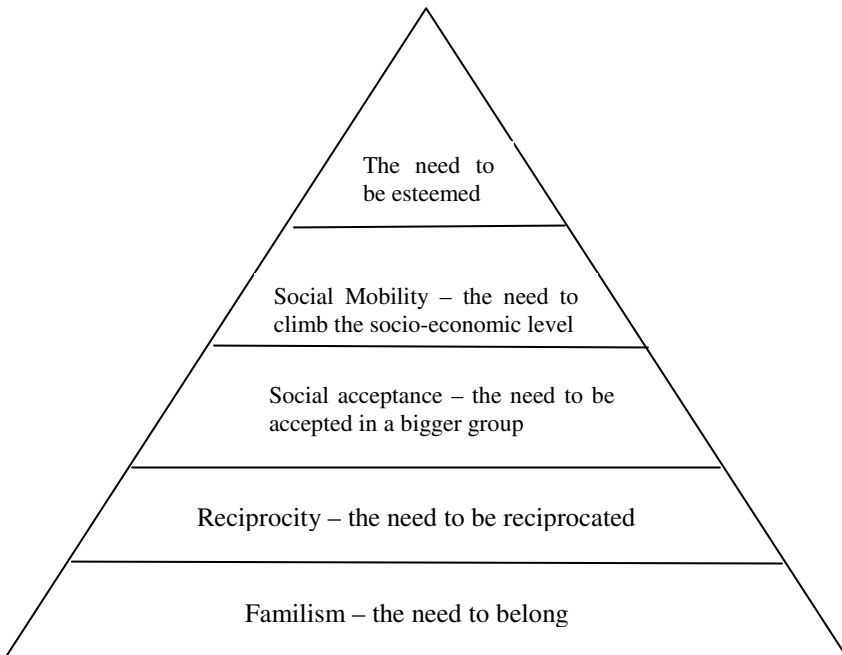


Fig. 4. The Filipino Hierarchy of Needs

The Filipino's value orientation tends to make him emphasize the familistic aspect of behavior. Relatives and members of family are often given first priorities in almost everything [9].

The Filipino stroke patient usually feels more the effect of helplessness due to the feeling of not being able to perform or act (as he usually did before his stroke) as expected in his social group. This is debilitating and could lead to depression in the Filipino patient. Social acceptance is one of the first three basic aims that predominantly motivate and control the behavior of the Filipinos [9]. This is defined by Andres as being taken by one's fellow for what he is or is believed to be and being that image in accordance with his status. The stroke patient who had previously enjoyed good rapport with his peers and social group would now find himself exerting effort to have full control of his limbs. His current predicament inadvertently segregates the patient

from the rest of his group. Hence, accessibility to a rehabilitating equipment that could help him regain his natural physique such as the 'robotic arm', would provide hope and a shield from desperation due to possible fall out from his social group.

Andres stated that acceptance is especially enjoyed when it includes an outward manifestation of approval that makes clear to the individual that he is liked by those with whom he deals, or is considered important by his superiors. During the patient's recuperation from stroke, this outward manifestation will be more of acceptance due to what he has done for them before (value of reciprocity) or what he is to them, particularly if there is a kindred relationship (value of familism). This reciprocity extended by the group members, which may appear more of a condescending attitude to Western perspective, is more automatic or natural to the Filipino who has respect for the weak, infirm and elderly. The patient becomes the recipient of this attitude of the Filipino which is more self-sacrificial in nature, caring and attending to the infirm even if actions lead to disruptions in one's schedule of activities.

This situation that the Filipino patient finds himself makes him question his social acceptance which is the third need in the hierarchy of Filipino needs. He therefore becomes secure in the knowledge that the first needs are satisfied and these could back him up in this situation. However, to regain social acceptance and to aspire for greater social mobility are needs that would be far from his reach with his present predicament. Based on Hofstede's study [10] of cultural differences among nations, he indicated that the Filipinos are highly masculine. This would mean that he is more aggressive and he is someone who would work hard for higher financial returns. Hence, one who has previously enjoyed the third and fourth rungs in the hierarchy of needs (social acceptance and mobility) and is working forward to satisfy higher needs would, compared with his counterparts in other nations, find it more frustrating to find oneself needing to satisfy these needs again. He could be viewed as having the stronger need to recover from the effects of the stroke in the shortest time possible.

Attainment of social acceptance is assisted by two intermediate values which are recognized as important and satisfying goals. These are smoothness of interpersonal relations, on the one hand, and sensitivity to personal affront, on the other [9]. The methods used to maintain smooth interpersonal relationship (SIR) include pakikisama (support of one's in-group), euphemisms and the use of go-between. The loss of social acceptance is guarded against two sanctions discouraging behavior descriptive of those relations. First, there is the universal sanction of hiya or being put to shame (loss of face). The second is amor propio (pride or love of one's self). Outcome of hiya is intense pain, which, if one's amor propio has been perceived to be bruised makes it excusable for the victim to aggressively retaliate or harm the source of his hiya. Teasing a stroke patient who could not perform simple tasks could hurt his pride (amor propio) which is a scenario that is unthinkable to a Filipino. In effect, the use of a robotic rehabilitation arm becomes expedient to him.

The product features of the robotic arm will be presented in the next section and their appropriateness in the light of Filipino values is discussed.

2.6 Robotic Arm Product Features Supported by Filipino Values

In this project, the machine is operated with the patient and a doctor or caregiver present. The session begins when the machine is turned on, and the patient places his

hand on the machine handle. Once that is done, the patient then starts by trying to perform the specified task of the selected mode, simple written instructions are given in the main menu of each mode. This is appropriate as it is known that Filipino elderly are not familiar with computer gadgets, moreover, playing computer games. In fact, Bayan Telecommunications, Inc. has just recently launched its computer literacy program for the aged. Its ad is a novel portrayal of a Filipino senior citizen well-versed in online happenings was a humorous take on one aspect of the “digital divide”. The robotic arm system somehow, with its simple instructions would not hinder to build up the interest of the elderly patient to reach good confidence on its use.

The arm is mainly controlled with a stepper motor and a microcontroller. The computer, using the Visual Basic 6 software, then creates a moving graphic (biofeedback) on a computer monitor based on the position of the arm. The motion of the graphic goes in synchrony with a game software also in Visual Basic to increase the patient’s motivation. In the robotic arm, only one arm at a time can be used for both modes therefore the required motion is limited to a maximum of 90 degrees per session. Whenever the patient is able to do it, a numeric point (or positive biofeedback) is given. Conversely, if the patient is not able to move it fully, the machine completes the motion for him. His hand would be guided to follow the proper motion expected. Again, biofeedback would be provided at the end of this motion. The process repeats over and over again until the set time is over. This process wherein the machine takes it upon itself to guide the patient’s hand when it could not move is considering the ‘hiya’ of the patient. It is highly possible that the patient would feel very awkward not being able to perform a very simple task. This is particularly true right after his stroke when he could barely move his limbs. As the patient goes through the process, it would not be apparent to others that he actually could barely perform the task. Left to himself, the designed process would help gauge his inadequacy by himself and lets him take control of his way to recovery. The important element here is that he is not put on the spot when he could not move his arm. This sensitive aspect was addressed by the robotic arm’s ability to guide the patient’s hand on the required movement.

The software can also generate a report for the benefit of the attending doctor, comprising both data inputs from the doctor such as patient descriptions and computer generated data such as performance records of the patient and simple numerical assessments. This immediate report allows the doctor to make a ready assessment of the state of the patient’s recovery. It revolutionizes the general practice of doctors who checks on the patient after recommending a series of physical therapeutic exercises. This designed process informs the doctor every time the patient uses the robotic arm. In the Philippines, the doctor is highly regarded in the society. One of the reasons is that he has the expertise that could lengthen the lives of the beloved elderly in the family. This set-up gives assurance to the family that the patient is well-attended to and his well-being fully monitored.

A sensor that detects temperature will also be actively used to ensure the safety and well-being of the patient. By default, although the machine will still be operating, the program will automatically stop when the patient exceeds 37.5 °C. This temperature when reached indicates that the body is gaining heat due to the patient’s exertion. This feature of the robotic arm equipment hinders the patient to overwork. The momentum gained by the patient particularly after many successes, as indicated by points obtained, may be difficult to reverse. This is a safety feature which takes care of the

elderly patients who may not be aware of the pressure of the exercise on their heart as well. This feature also gives assurance to the family members that their elderly relative is given the best care possible. In the robotic arm, this safety feature proves its soundness as a rehabilitation equipment.

3 Conclusion

The robotic arm rehabilitation machine with biofeedback was developed with the intent on motivating the stroke patient to actively involve himself in his progressive recovery. The product was developed with the consideration of Filipino value system which generally supports the infirm and elderly. Other elements of this value system also promote the product design features of the robotic arm. This new approach in product design provides a more customer-focused strategy which does not only appeal to the patient himself but to the caring family members as well.

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