Analyzing the Human-Robot Interaction Abilities of a General-Purpose Social Robot in Different Naturalistic Environments

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Abstract. The main goal of this article is to report and analyze the applicability of a general-purpose social robot, developed in the context of the RoboCup @Home league, in three different naturalistic environments: (i) home, (ii) school classroom, and (iii) public space settings. The evaluation of the robot's performance relies on its degree of social acceptance, and its abilities to express emotions and to interact with humans using human-like codes. The reported experiments show that the robot has a large acceptance from expert and non-expert human users, and that it is able to successfully interact with humans using human-like interaction mechanisms, such as speech and visual cues (particularly face information). It is remarkable that the robot can even teach children in a real classroom.

Keywords: Human-Robot Interaction, Social Robots.

1 Introduction

Social robots are becoming of increasing interest in the robotics community. A social robot is a subclass of a mobile service robot designed to interact with humans and to behave as a partner, providing entertainment, companion and communication interfaces. It is expected that the morphology and dimensions of social robots allow them to adequately operate in human environments. It is projected that social robots will play a fundamental role in the next years as companions for elderly people and as entertainment machines.

Among other abilities, social robots should be able to: (1) move in human environments, (2) interact with humans using human-like communication mechanisms (speech, face and hand gestures), (3) manipulate objects, (4) determine the identity of the human user (e.g. "owner 1", "unknown user", "Peter") and its mood (e.g. happy, sad, excited) to personalize its services, (5) store and reproduce digital multimedia material (images, videos, music, digitized books), and (6) connect humans with data or telephone networks. In addition, (7) they should be empathic (humans should like them), (8) their usage should be natural without requiring any technical or computational knowledge, and (9) they should be robust enough to operate in natural

J. Baltes et al. (Eds.): RoboCup 2009, LNAI 5949, pp. 308–319, 2010.

environments. Social robots with these abilities can assist humans in different environments such as public spaces, hospitals, home settings, and museums. Furthermore, social robots can be used for educational purposes.

Social robots should have acceptance by every kind of human user, including non-expert ones as elderly and children. We postulate that in order to have acceptance, it is far more important to be empathic and to produce sympathy in humans than to have an elaborated and elegant design. Moreover, to produce effective interaction with humans, and even enable humans to behave as if they were communicating with peers, it has been suggested that the robot body should be "based on a human's" [5] or being human-like [3]. We propose that it is important to have a somehow anthropomorphic body, but that to have a body that exactly look likes a human body is not required. Many researchers have also mentioned the importance that when interacting with humans, the robot tracks or gazes the face of the speaker [7][8][6][4]. We also believe that these attention mechanisms are important for the human user. In particular, the detection of the user's face allows the robot to keep track of it, and the recognition of the identity of the user's face allow the robot to identify the user, to personalize its services and to make the user feel important (e.g. "Sorry Peter, can you repeat this?"). In addition, it is also relevant that the interaction with the robot has to be natural, intuitive and based primarily on speech and visual cues (still some humans do not like to use standard computers, complex remote controls o even cell phones).

The question is how to achieve all these requirements. We believe that they can be achieved if the robot has a simple and anthropomorphic body design, it is able to express emotions, and it has human-like interaction capabilities, such as speech, face and hand gestures interaction. We also believe that it is important that the cost of a social robot be low, if our final goal is to introduce social robots in natural human environments, where they will be used by normal persons with limited budgets. Taking all this into consideration we have developed a general-purpose social robot that incorporates these characteristics.

The main goal of this article is to report and analyze the applicability of the developed robot in three different naturalistic environments: (i) home, (ii) school classroom and (iii) public space settings. The evaluation of the robot's performance relies in the robot's social acceptance, the ability of the robot to express emotions, and the ability of the robot to communicate with humans using human-like gestures. The article is structured as follows. In section 2, the hardware and software components of the social robot are briefly outlined. We emphasize the description of the functionalities that allow the robot to provide human-like communication capabilities and to be emphatic. Section 3 describes the robot applicability in three different naturalistic environments. Finally, in sections 4 and 5, discussion and some conclusions of this work are given.

2 Bender: A General-Purpose Social Robot

The main idea behind the design of Bender, our social robot, was to have an open, flexible, and low-cost platform that provides human-like communications capabilities, as well as empathy. Bender has an anthropomorphic upper body (head, arms, chest), and a differential-drive platform provides mobility. The electronic and mechanical hardware components of the robot are described in [12]. A detailed description of the robot as well as pictures and videos can be found in its personal website: http://bender.li2.uchile.cl/. Among Bender's most innovative hardware components to be to mention is the robot head, which incorporates the ability of expressing emotions (see figure 1).

The main components of the robot's software architecture are shown in figure 2. The *Speech Analysis & Synthesis* module provides a speech-based interface to the robot. Speech Recognition is based on the use of several grammars suitable for different situations instead of continuous speech recognition. Speech Synthesis uses Festival's Text to Speech tool, dynamically changing certain parameters between words in order to obtain a more human-like speech. This module is implemented using a control interface with a CSLU toolkit (http://cslu.cse.ogi.edu/toolkit/) custom application. Similarly, the *Vision* module provides a visual-based interface to the robot. This module is implemented using algorithms developed by our group. The *High-Level Robot Control* is in charge of providing an interface between the *Strategy* module and the low-level modules. The first task of the *Low-Level Control* module is to generate control orders to the robot's head, arm and mobile platform. The *Emotions Generator* module is in charge of generating the specific orders corresponding to each emotion. Emotions are called in response to specific situations within the finite-state machine that implements high-level behaviors. Finally, the *Strategy* module is in charge of selecting the high-level behaviors to be executed, taking into account sensorial, speech, visual and Internet information. Of special interest for this article are the capabilities for face and hand analysis included in the *Vision* module. The *Face and Hand Analysis* module incorporates the following functionalities: face detection (using boosted classifiers) [16][18], face recognition (histogram of LBP features) [1], people tracking (using face information and Kalman Filters) [14], gender classification using facial information [17], age classification using facial information, hand detection using skin information and recognition of static hand gestures [2].

Bender's most important functionalities are listed in table 1. All these functionalities have been already successfully tested as single modules. Table 2 shows quantitative evaluations of the human-robot interaction functionalities, measured in standard databases. As it can be observed in these databases, the obtained results are among the best-reported ones. This is an important issue, because we would like that our social robot has the best tools and algorithms when interacting with people. For instance, we do not want that the robot to have problems by detecting people when immersed in an environment with variable lighting conditions.

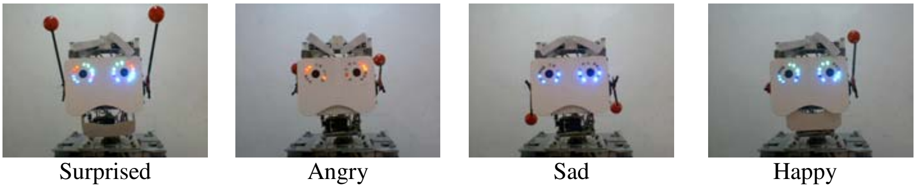
Surprised Angry Sad Happy

Fig. 1. Facial expressions of Bender

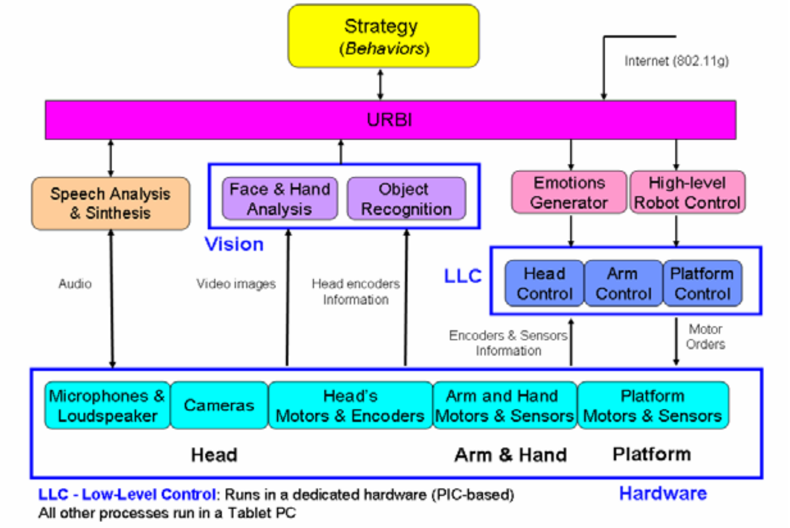

Fig. 2. Software architecture. In the bottom the hardware components: platform, head, and arm. In an upper level, low-level control processes running in dedicated hardware. All high level processes run in a tablet PC.

Table 1. Bender's main functionalities

Ability	How is achieved
Mobility	A differential-drive platform provides this ability.
Speech recognition and synthesis	CSLU toolkit (http://cslu.cse.ogi.edu/toolkit/).
Face detection and recognition	Face and hand analysis module.
Gender and age determination using facial information	Face and hand analysis module.
Hand gesture recognition	Face and hand analysis module.
General purpose object recognition	SIFT-based object recognition module
Emotions expression	Anthropomorphic 7 DOF mechatronics head.
Object manipulation	A 3 DOF arm with 3, 2 DOF fingers.
Information visualization	The robot's chest incorporates a 12 inch display
Standard computer inputs (keyboard and mouse)	The chest's display is *touch screen*. In addition, a virtual keyboard is employed in some applications.
Internet access	802.11b connectivity.

3 Applicability in Naturalistic Environments

3.1 Real Home Setting

One of the main goals behind the development of our social robot is to use it as an assistant and companion for humans in home settings. The idea is that the robot will be able to freely interact with non-expert users in those environments. Naturally, we know that we need to follow a large process until achieving this goal. In 2006 we decided that a very appropriate way to achieve this was to regularly participate in the RoboCup@Home. RoboCup@Home focuses on real-world applications and human-machine interaction with autonomous robots in home settings. Tests are related with manipulation of typical objects that can be found in a home-like environment, with navigation and localization inside a home scenario, and with interaction with humans. Our social robot participated in 2007 and 2008 in the RoboCup@Home world competition, and in both years it got the RoboCup @Home Innovation Award as the most innovative robot in competition. The Technical Committee members of the league decide this award. The most appreciated robot's abilities were its empathy, ability to express emotions, and human-like communications capabilities.

Table 2. Evaluation of some selected Bender's functionalities in standard databases

	Database	**Results**	**Comments**
Face Detection (1)			
- Single face	BioID	DR=95.1%, FP=1	Best reported results
- Single face	FERET	DR=98.7%, FP=0	NoRep
- Multiple faces	CMU-MIT	DR=89.9%, FP=25	4th best reported results
- Multiple faces	UCHFACE	DR=96.5%, FP=3	NoRep
Face Tracking (2)			
- Multiple faces	PETS-ICVS 2003	DR=70.7%, FP=88 (set A) DR=70.2%, FP=750 (set A)	Best reported results.
Eyes Detection (1)			
- Single Face	BioID	DR=97.8%, MEP=3.02	Best reported results
- Single Face	FERET	DR=99.7%, MEP =3.69	NoRep
- Multiple faces	UCHFACE	DR=95.2%, MEP =3.69	NoRep
Gender Classification (1)			
- Single Face	BioID	CR: 81.5%	NoRep
- Single Face	FERET	CR: 85.9%	NoRep
- Multiple faces	UCHFACE	CR: 80.1%	NoRep
Face Recognition			
- Standard test (3)	FERET *fafb*	Top-1 RR=97%	Among the best reported results
- Variable Illumination (4)	YaleB	7 individuals per class, Top-1 RR=100% 2 individuals per class, Top-1 RR=96.4%	Best reported results
- Variable Illumination (4)	PIE	2 individuals per class, Top-1 RR=99.9	Best reported results
Hand Gesture Recognition (5)			
- Variable illumination	Own Database, real-word videos, 4 static gestures	RR=70.4%	NoRep

(1) Reported in [18]; (2) Reported in [14]; (3) Reported in [1]; (4) Reported in [13]; (5) Reported in [2]. DR: Detection Rate; FP: Number of False Positives; RR= Recognition Rate; CR= Classification Rate; MEP; Mean Error in Pixels; NoRep: No other reports in the same dataset.

3.2 Classroom Setting

Robotics is a highly motivating activity for children. It allows them to approach technology both amusingly and intuitively, while discovering the underlying science principles. Indeed, robotics has emerged as a useful tool in education since, unlike many others, it provides the place where fields or ideas of science and technology intersect and overlap [11]. With the objective of using social robots as a tool for fostering the interest of children in science and technology, we tested our social robot as lecturer for school children in a classroom setting. The robot gave talks to schoolchildren of 10-13 years old. Altogether 228 schoolchildren participated in this activity, and at each time one complete course assisted to the talk in a multimedia classroom (more than 10 talks were given by the robot). The duration of each talk was 55 minutes, and it was divided in two parts. In the first part the robot presented itself, and talked about its experiences as a social robot. In the second part the robot explained some basic concepts about renewable energies, and about the responsible use of energy. After the talk students could interact freely with the robot. The talk was given using the multimedia capabilities of the robot; speech and multimedia presentation, which was projected by the robot (see pictures in figure 3).

After the robot's lecture the children, without any previous advice, answered a poll regarding their personal appreciation of the robot and some specific contents mentioned by the robot. In the robot evaluation part, the children were asked to give an overall evaluation of the robot. On a linear scale of grades going from 1 to 7, the robot was given an average score of 6.4, which is about 90%. In the second part children evaluated the robot's presentation: 59.6% rated it as excellent, 28.1% as good, 11.4% as regular, 0.9% as bad, and 0% as very bad. The third question was, "Do you think that it is a good idea for robots to teach some specific topics to schoolchildren in the future?" 92% of the children answered yes. In the technical content evaluation part, the first three questions were related to energy sources (classification of different energy sources as renewable or non- renewable, availability of renewable sources, and indirect pollution produced by renewable sources). The fourth question asked about the differences between rechargeable and non-rechargeable batteries, and the fifth question asked about the benefits of the efficient use of energy. The percentage of correctness of the children's answers to each of the five technical content questions is shown in Table 3. The overall percentage of correct answers was 55.4%.

In summary, we can observe that children had a very good evaluation of the robot (6.4 over 7), and that 87.7% of them evaluated the presentation as excellent or good. They also have a very favorable opinion about the use of robots as lecturers in a

Table 3. Percentage of correctness of the children answers to the 5 technical questions

Technical Questions	Correctness
TQ1	75.9%
TQ2	33.7%
TQ3	31.6%
TQ4	75.0%
TQ5	60.6%
Overall	55.4%

classroom environment (92%). Moreover, the children were able to learn some basic technical concepts (the overall percentage of correct answers was 55.4%), although they just heard them once from a robot. The main goal of this technical content part of the evaluation was just to see if the children could learn some basic content from the robot, and not to measure how well they learned it. Therefore, control experiments with human instructors were not carried out. This will be part of the future work. Finally, it is important to stress that the robot was able to give its talk and to interact with the children without any human assistance.

Fig. 3. Bender giving talks to schoolchildren

3.3 Public Space Setting

We tested the applicability of our social robot in a public space setting. The main idea of the experiment was to let humans interact freely with the robot, using only speech and visual cues (face, hand gestures, facial expressions, etc.). The robot did not moved by itself during the whole experience, in order to avoid any collision risks with the students, therefore it needed to catch the people's attention just using speech synthesis, visual cues and other strategies such as complaining about being alone, bored, or calling far-away detected people. The robot was placed in a few different public spaces inside our university campus (mainly building's halls), and the students passing through these public spaces could interact with the robot, if they wanted (see pictures in figure 4). When the robot detected a student in its neighborhood, it asked the student to approach and have a little conversation with him. The robot presented itself, then it asked some basic information to the student, and afterwards it asked the student to evaluate its capabilities to express emotions. Finally, after the evaluation, the robot thanked the student and the interaction finished. To evaluate the ability of the robot to express emotions, the robot randomly expressed an emotion, and it asked the student to identify the emotion. The student gave its answer using the touch screen (choosing one of the alternatives).

This process was repeated four times, to allow the student to evaluate different emotions. We decided that the human users gave their answer using the touch screen, to be sure that the speech recognition mistakes would not affect the experiment. This was the only time that the interaction between the robot and the human was not based on speech or visual cues. In all moments, no external human assistance was given to the robot's users. After the human–robot interaction finished, and the humans leaved the robot's surround, they were asked to evaluate its experience using a poll.

In all experiments the robot was left alone in a hall, and the laboratory team observed the situation several meters away. Our first observation was that from the total of students that passed near the robot, about 37% modified their behavior and approached the robot. 31% of them interacted with the robot, the rest just observed it. The total number of students that interacted with the robot was 83. The age range was 18 to 25 years old, and the gender distribution was 70% males and 30% females. Out of the 83 students, 74.7% finalized the interaction, and 26.3% leaved before finishing. The main reasons for leaving prematurely were: (i) the students were not able to interact with the robot properly (speech recognition problems, see discussion section), (ii) they did not have enough time to make the emotions' evaluation, or (iii) they were not interested in making the evaluation. The mean interaction time of the humans that finalized the interaction, including the emotions' evaluation, was 124 seconds.

In table 4 is displayed the recognition rate of the different expressions. It can be observed that the overall recognition rate was 70.6%, and that all expressions, but "happy" have a recognition rate larger than 75%. In table 5 and 6 the results of the robot's evaluation poll, made by the users after interacting with the robot are presented. It should be remembered that only the 74.7% of the users that finished the interaction with the robot, answered the poll. As it can be observed in tables 5 and 6, 83.9% of the users evaluate the robot's appearance as excellent or good, 88.5% evaluate the robot's ability to express emotions as excellent or good, and 80.7% evaluate the robot's ability to interact with humans as excellent or good. In addition, 90% of them think that it is easy to interact with the robot, 84% believe that the robot is suitable to be a receptionist, museum guide or butler, and 67% think that the robot can be used with educational purposes with children. It should be mentioned that the whole experiment was carried out inside an engineering campus, and that therefore the participants in the test were engineering students, who with a high probability enjoy technology and robots. On the other hand, we believe that as expert users in technology, they can be more critical about robots than standard users. Nevertheless, we think that the obtained results show than in general terms the social robot under evaluation has a large acceptance in humans, and that its abilities to interact with humans using speech and visual cues, as well as its ability to express emotions, are suitable for free human-robot interaction situations in naturalistic environments.

Table 4. Recognition rate of robot's facial-expressions

Expression	Correctness
Happy	51.0%
Angry	76.5%
Sad	78.4%
Surprised	76.5%
Overall	70.6%

Table 5. Human's evaluation of the robot's appearance and interaction abilities

	Excellent	**Good**	**Regular**	**Bad**	**Very Bad**
Robot appearance	30.7%	53.2%	14.5%	1.6%	0%
Ability to express emotions	31.1%	57.4%	8.2%	3.3%	0%
Ability to interact with humans	17.8%	62.9%	17.7%	1.6%	0%

Table 6. Human's evaluation of the robot's applicability and simplicity of use

	Yes	No
Do you think that it is easy to interact with the robot?	90%	10%
Do you think that the robot is suitable to be a receptionist, museum guide or butler?	84%	16%
Do you think that the robot can be useful in tasks related with children interaction?	67%	33%

Fig. 4. Bender interaction with students in a public space inside the university

4 Discussion

Evaluation Methodology. There exist different approaches to evaluate the performance of social robots when interacting with humans. Although, isolated algorithms' performance should be measured (e.g. recognition rate of a face recognition algorithm), it is also necessary to analyze how robots affect humans. Some researchers have proposed to employ quantitative measures of the human attention (attitude [10], eye gaze [9], etc.) or body movement interaction between the human and the robot [5]. We do believe that acceptance and empathy are two of the most important factors to be measured in a human-robot interaction context, and that these factors can be measured using poll-based methods that express the user's opinion. The described social robot has been evaluated by about 300 people with different backgrounds (228 schoolchildren, 62 engineering students, and 5 international researchers in the RoboCup @Home competitions), which validates the obtained results.

Evaluation of robot capabilities. As it can be observed in table 2, the visual-based human-robot interaction functionalities of the robot, measured in standard databases are among the best-reported ones. We believe that this is very important, because the robot should have robust tools and algorithms to deal with dynamic conditions in the environment. In addition, the robot has received two innovation awards from the service-robot scientific community, which indicates that the robot theoretically is able to adequately interact with people.

Robot Evaluation when interacting with people. In our experiments with children in a real classroom setting, we observed that children gave a very good evaluation to the robot, and that 87.7% of them evaluated its presentation as excellent or good. They have also a very favorable opinion about the use of robots as lecturers in a classroom environment. We can conclude that the robot achieved the acceptance of the children (10-13 years old), who for the first time had the opportunity to interact with a robot. The robot was able to give its talk and to interact with the children without any human assistance. We conclude that the robot is robust enough to interact with non-expert users in the task of giving talks to groups of humans. In addition, the children were able to learn some basic technical concepts from the robot (55.4% correct answers to 5 technical questions). It should be stressed that the robot presentation was a standard lecture, without any repetition of contents. Besides, it should be observed that the robot, unlike a human teacher, can not detect distracted children in order to call for their attention, and also can not achieve the same level of expressivity neither in the speech or the gestures, leaving it only with his empathy and other mechanisms such as simulating breathing or moving the mouth while talking to catch the listener's attention. These results encourage us to further explore in the relevance of an appealing human robot interaction interface. Naturally, it seems necessary to carry out a comparative study of the performance of robot-teachers against human-teachers, and to analyze the dependence of the results on the specific topics that are to be taught (technical topics, foreign language, history, etc.).

In our experiments in public space settings we tested the ability of the social robot to freely interact with people. The experiments were conducted in different building's halls inside our engineering college. 37% of the students passing near the robot approached it; 31% of them interacted directly with the robot. In all cases the robot actively tried to attract the students, by talking to them. It was interesting to note that 26.3% of the students that interacted with the robot leaved before finishing the interaction. One of the main reasons for leaving was that the students were not able to interact properly with the robot, due to speech recognition problems. Our speech recognition module has limited capabilities, it is not able to recognize unstructured natural language, and the recognition is perturbed by the environmental noise. This is one of the main technical limitations of our robot, and in general of other service robots. Nevertheless, 74.7% of the students finished the emotion's evaluation that the robot proposed them, with a mean interaction time of 124 seconds.

Before carrying out these experiments we had the qualitative impression that, the emotions that our robot could generate were adequate, and that a human could understand them. The quantitative evaluation obtained in the experiments showed us that this perception was correct, and the humans can recognize correctly the robot's expression in 70.6% of the cases. This overall result can be improved if we design a new "happy" expression, which was recognized in only 51% of the cases. Although the mechanics of the robot head imposes some limits to the expressions that can be generated by the robot (limitation in the number of degrees of freedom in the face), we believe the current expressions are rich enough to produce empathy in the users. We have seen these in all reported experiments, and also in non-reported interactions between the robot and external visitors in our laboratory.

The acceptance of the robot by the engineering students, as in the case of the children, was high (83.9% evaluated the robot's appearance as excellent or good, 88.5% evaluated the robot's ability to express emotions as excellent or good, 80.7% evaluate the robot's ability to interact with humans as excellent or good). In addition, 90% of the students think that it is easy to interact with the robot, and 84% and 67% of the students think that the robot can be used as an assistant or with educational purposes, respectively. We believe that this favorable evaluation is due to the fact that: (i) the robot has an anthropomorphic body, (ii) it can interact using human-like interaction mechanisms (speech, face information, hand gestures), (iii) it can express emotions, and (iv) when interacting with a human user it tracks his/her face.

5 Conclusions

The main goal of this article was to report and analyze the applicability of a low-cost social robot in three different naturalistic environments: (i) home setting, (ii) school classroom, and (iii) public spaces. The evaluation of the robot's performance relied in the robot social acceptance, and its abilities to express emotions and interact with humans using human-like codes. The experiments show that the robot has a large acceptance from different groups of human users, and that the robot is able to interact successfully with humans using human-like interaction mechanisms, such as speech and visual cues (specially face information). It is remarkable that children learnt something from the robot despite its limitations.

From the technical point of view, the visual-based human-robot interaction functionalities of the robot, measured in standard databases are among the best-reported ones, and the robot has received two innovation awards from the scientific community, which indicates that the robot is able to adequately interact with people. However, one of the main technical limitations is the speech recognition module, which should be improved.

As future work we would like to further analyze the teaching abilities of our robot. In general terms, we believe that more complex methodologies should be used to measure how much the children learn with the robot, and how is this learning compared with the case when children learn with a human teacher.

Acknowledgements

This research was partially funded by FONDECYT project 1090250, Chile.

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