A Companion Technology for Cognitive Technical Systems

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Abstract. The Transregional Collaborative Research Centre SFB/TRR 62 *"A Companion Technology for Cognitive Technical Systems"*, funded by the German Research Foundation (DFG) at Ulm and Magdeburg sites, deals with the systematic and interdisciplinary study of cognitive abilities and their implementation in technical systems. The properties of multimodality, individuality, adaptability, availability, cooperativeness and trustworthiness are at the focus of the investigation. These characteristics show a new type of interactive device which is not only practical and efficient to operate, but as well agreeable, hence the term "companion". The realisation of such a technology is supported by technical advancement as well as by neurobiological findings. Companion technology has to consider the entire situation of the user, machine, environment and (if applicable) other people or third interacting parties, in current and historical states. This will reflect the mental state of the user, his embeddedness in the task, and how he is situated in the current process.

1 Research Issues

Technical systems of the future are *Companion*-systems - cognitive technical systems, with their functionality completely individually adapted to each user: They are geared to his abilities, preferences, requirements and current needs, and they reflect his situation and emotional state. They are always available, cooperative and trustworthy, and interact with their users as competent and cooperative service partners.

Guided by this vision, in the Transregional Collaborative Research Center SFB/TRR 62, an interdisciplinary consortium of computer scientists, engineers, physicians, neuroscientists and psychologists, are involved with the systematic exploration of cognitive abilities and their realization in technical systems. Here, the properties of individuality, adaptability, availability, cooperativeness and trustworthiness are in the center of the investigation. The aim is to realize these so-called *companion properties* by cognitive processes in technical systems, and

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to examine them using psychological behavioral models and functional models of brain mechanisms. This will be the foundation for a technology within the realm of affective computing [1] in which human users are offered a completely new dimension in dealing with technical systems. The SFB/TRR 62 complements here the work of other consortia. For example, the EU 6^{th} framework consortium HUMAINE [2] aims at the development of emotion-oriented systems, however a backbone companion architecture was not aimed at. The EU 6^{th} framework COMPANIONS consortium [3] focuses on virtual conversational agents, however neurobiological foundations and planning and strategy aspects were not investigated. Neurobiologically motivated modelling however was investigated by some of the SFB/TRR 62 members and colleagues in the NIMITEK project [4]. These examples are of course non-exhaustive and merely illustrate that other prominent activities with related foci exist.

The Transregional Collaborative Research Centre SFB/TRR 62 was installed at 01. January 2009 by the German Research Foundation (DFG) at sites Ulm and Magdeburg. At the University of Ulm, the Otto-von- Guericke University in Magdeburg, and the Leibniz-Institute for Neurobiology in Magdeburg, 80 scientists are now working within this project.

2 Research Areas

The research program to develop a *Companion* technology for cognitive technical systems includes interdisciplinary research in the methodological basis of the three key areas of *planning and decision-making*, *interaction and availability* and *situation and emotion*. The relevant research questions are investigated from two complementary perspectives on the interaction of user and system:

– The *system perspective* focuses on the structural aspect, i.e. the construction of cognitive functional units and the realization of *companion properties* by these functional units.
– The *user's perspective* examines the effect of system behavior to the user. This manifests itself in the mental model, which the users build up of a *Companion*-system, and in the user's response to the system.

2.1 Planning and Decision Making

The central cognitive processes of planning, reasoning, and decision making are the basis of action and interaction between users and technical systems. To unveil these processes, the development of strategies of action in biological and technical systems are being investigated, as are the effects of system behavior on the user behavior and its effects on the interaction process. The overall goal is to develop, to use and to test knowledge-based methods which enable a *Companion*-system to support users of applications and services in their actions and decisions in a comprehensive, professional and individual manner. A *Companion*-system should be able to provide solutions for complex tasks – all by itself or in cooperation with the user –, using targeted and traceable strategies, and, in dialog with the user, give decision support and action recommendations. These strategies are based on the user's current interests, on his abilities and preferences; they take into account his emotional state, and adapt the support services to the current environmental situation.

The SFB/TRR 62 deals with the topics of action planning, strategy development and decision finding from both a system and user perspective. To this end, it is quite natural and adequate to rely on a technical equivalent of the user's cognitive abilities, namely on AI planning [5].

Assistance functionalities required for supporting individual users of a technical system include (1) generating a plan of action for a specific user that respects her preferences and emotional state and advising her to carry out the plan in order to achieve a current task, (2) instructing the user on how to escape from a situation where the execution of this plan unexpectedly failed, and (3) justifying and explaining the proposed solution plan in an adequate manner. These assistance functionalities can be provided by an approach to user-centered planning that relies on a domain-independent hybrid planner, a plan repair component, and a plan explanation facility [6].

Plan generation can be performed by reasoning about the preconditions and effects of actions as in partial order causal link (POCL) planning [7]. Hierarchical task network (HTN) planning [8] allows for the use of pre-defined standard solutions and with that enables the exploitation of expert knowledge in solution discovery. By smoothly integrating both paradigms, hybrid planning [9] is particularly well-suited for solving complex real-world planning problems.

When aiming to support human users in a *Companion*-like manner, one of the key aspects is the *individualization* of the recommended course of action. This is achieved by respecting not only the mandatory needs of the person to assist, but also her *user preferences* – solution criteria which are not mandatory, but which should be met if ever possible. Approaches to preference-based planning use (1) temporal constraints on state features as the standard notation for expressing desired, but non-mandatory, plan properties, and (2) heuristic search in the space of states in order to find preferred plans [10]. In contrast to that we have developed an extension to standard POCL techniques that allows to effectively estimate plan quality w.r.t. user preferences [11].

In the context of *Companion*–systems, an additional challenge has to be met, however: Information about the user state, just like information about the world state, depends on sensory input and is thus only partially observable and inherently uncertain. In order to address partial observability, relational partially observable Markov decision processes (POMDPs) can be employed [12]. They allow to handle complex domain dynamics and are thus appropriate to represent decision problems that have to solved when users are to be assisted while operating a technical system. To cope with the accruing uncertainty, we developed a novel approach to hierarchical planning under partial observability in relational domains [13], which combines hierarchical task network planning with the finite state controller (FSC) policy representation for partially observable Markov decision processes.

Exceptional events can invalidate a plan at execution time. In user-centered planning, a possible remedy is to start from the original plan and try to replace the invalidated parts without touching the unaffected ones, thus ensuring plan stability [14]. But still, having to follow a repaired plan in most cases implies a change of strategy. As this, in general, is a pivotal element of interaction between a *Companion*–system and its user, we investigate the neurophysiological foundations of strategy change in biological systems. We use a suitably designed animal model, which is sufficiently complex to include relevant aspects of strategy change during subject-computer interactions and at the same time sufficiently simple to allow detailed neurophysiological analysis. An important question is, whether and how reinforcement-evaluating brain structures, like the ventral tegmental area (VTA) and lateral habenula (LHb), contribute to a change of behavioral strategy. A change of strategy can be emulated by a contingency reversal of two different acoustic stimuli in a discrimination behavioral task. In order to give an answer to this question we needed to investigate the influence of these brain structures in avoidance learning. A series of experiments were conducted and their results support the general conclusion that VTA and LHb influences the acquisition of an avoidance task and therefore are relevant brain structures for learning strategy changes. Furthermore, it has been confirmed, that stimulation in VTA and LHb has opponent effects on avoidance learning. During acquisition, LHb stimulation impaired avoidance, while VTA stimulation improved it [15]. These neurobiological findings enter into a declarative model that serves to estimate how difficult the management of a particular strategy change would be for a certain individual [16].

Knowledge Base. The knowledge base of a *Companion* system stands at a central point – between perception and action. As such, its task is to incorporate information gained by the sensory system, enhancing it with various kinds of background knowledge, and produce an, as accurate as possible, prediction that can be used as a basis of action selection. The main functional units a knowledge base has to serve are depicted in Figure 1. As can be seen there, information is exchanged with modules working with both symbolic and sub-symbolic data. Perception is rooted in the sub-symbolic processing of audio-visual sensor streams or biosignals taken from respective sensors. The interaction manager maintains communication with the user via multiple modalities and is both a producer of a symbolic stream of observations as well as a consumer of inferred information. The planning system needs to be provided with declarative background and world knowledge.

In order to properly combine declarative expert knowledge with sub-symbolic training data to obtain the required world model, we decided to use Markov Logic [17] as a means to implement knowledge bases of *Companion* systems. So far we have focused on efficiently drawing probabilistic inferences in a dynamic environment while still being able to leverage the expressive power of logic [18]. We also aim at improving sub-symbolic methods for recognizing complex

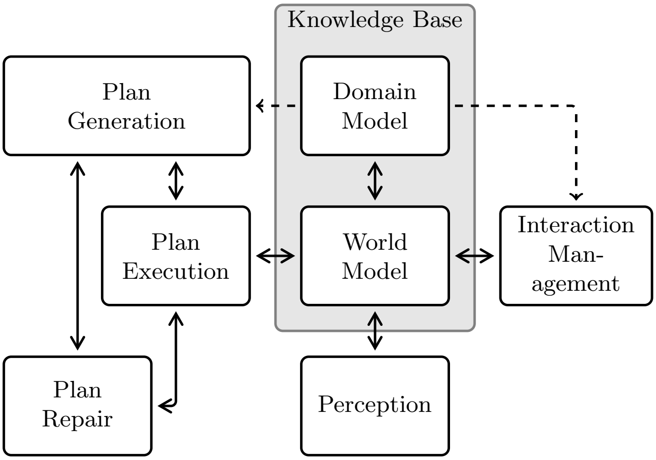

Fig. 1. The Role of the Knowledge Base

dynamic patterns, like activities performed by humans, using a layered Hidden Markov Model architecture [19].

2.2 Interaction and Availability

Humans interact with their environment using all senses, and their cognitive and motor skills. Accordingly a computer-based system, if seen as a peer communication and interaction partner to the human, will also be required to use various input and output channels. Moreover, if the system is going to show *Companion* properties it has to adapt its dialog and interaction strategies and behavior to the environmental situation and to the human's current tasks and emotional state. Dialog and interaction has to be constantly available, perform in a cooperative style and finally should be recognized as a credible, trustworthy interaction of a *Companion*.
Bearing this in mind, it is obvious that future systems showing these *Companion* properties cannot be modeled and developed as current interactive systems are being devised. Interaction needs to be multimodal on multiple devices, situative and individualized, depending on the environmental state and on the human's tasks, habits and emotions. Thus we brought together researchers from neuro biology, from spoken dialog management and from Human–Computer–Interaction computer science in order to understand the requirements in a holistic view and to devise a system approach guided by these expertises.

Neuro-biological Findings. One fundamental rule in interactions is the need for the sender to obtain information that a message has been received, i.e. the subjective sense of completion of an action [20]. In human conversation, language as well as non-verbal means satisfy this expectation [21]. Technical systems are usually not equipped with comparable competences and therefore must rely more heavily on quick response times to indicate that a user action has been processed. We observed in a functional imaging study that an unexpected delay of feedback by only 500 ms has an equally strong effect on brain activation as a complete omission of the feedback. The increase in activity elicited by delayed and omitted feedback compared with immediate feedback was mainly observed in brain regions known to be involved in attention and action control which suggests that additional neural resources are needed in such potentially irritating situations [22] [23].

Another important aspect in human communication is the fact that it is not only important *what* is said but also *how* it is said, i.e. by means of prosodic modulation. Therefore, we tested the effects of motivational prosody in a learning task by employing short pre-recorded verbal comments (e.g. right, wrong, yes, no) with either neutral or motivational prosody (i.e. praising, blaming). We found that motivational feedback produced a significantly steeper learning curve than feedback with neutral prosody. Additionally, we showed that both of the naturally spoken feedback conditions led to a significantly better learning performance compared with computer-synthesized speech.

Such findings are directly transferred in the project into the technical models, architectures and functionalities as suggested by [24].

Technical Models for Human-Companion Interaction. A *Companion*–system will use context data obtained from diverse sensors via different channels and it will potentially provide interaction with the user through multiple devices using multiple modalities. This multitude of possibilities offers a new perspective for adaptive multimodal interaction and flexible dialog management requiring independent interaction concept for *Companion*–systems as a cross-section technology. Moreover the concept has to provide for run-time adaptivity, because devices, environmental and user statuses define the final user interface only at runtime. To meet this requirement our *Companion* architecture is based on a modified Arch/Slinky meta-model [25]. This Stormy Tree meta-model (Fig. 2) extends the Arch/Slinky model for multimodal interaction. The forked branches on the right side represent different concepts for multimodal interaction. The mediation of different input streams is coordinated by an adaptive fusion process and engine. The multimodal output is coordinated by a rule-based fission engine which selects appropriate information objects according to the goal model being described next.

The hierarchical and modality independent dialog structure is built upon different components (Fig. 3). First of all, goals are the main building blocks of the hierarchy and represent abstract tasks to be accomplished. The top level goals correspond to plan actions from the planning component. For the human-companion interaction process these goals are hierarchically refined using subgoal links to model parallelism, and are horizontally connected using next-goal links to model sequences. To control goal execution, and enable adaptive dialog strategies, goals can be connected to variables via guards and effects. Guards allow testing for specific values before a goal is executed, while effects represent value assignments to variables when a goal is completed. Each leaf-level goal

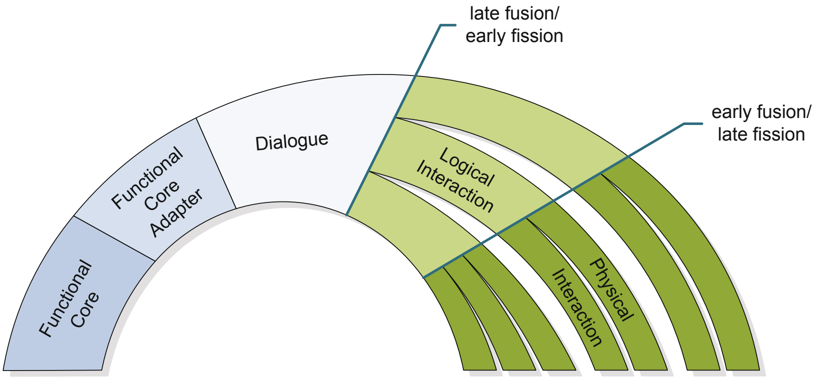

Fig. 2. Stormy Tree Model as an architectural meta model for Human-Companion Interaction

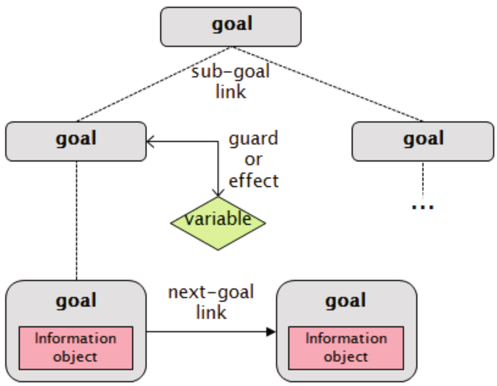

Fig. 3. Goal-based model for dialog and interaction structure

contains information objects as modality independent information, which has to be communicated towards or received from the user.

2.3 Situation and Emotion

Humans can assess situations with emotionally and intentionally acting partners in their entirety and context-dependently. This ability is also to be investigated as key to *Companion*-systems, which makes it another central concern of the SFB/TRR 62. The goal is to obtain a dynamic detection and modeling of the situatedness - location in space, movement, orientation, attention, etc. - and of the individual emotionality in dealing with technical systems. In many typical situations of human-computer interaction it may not be necessary to identify proper emotions (apart from the problem that there seems to be no universally agreed definition of them), instead the system has to identify the user's disposition towards the current interaction with the system in categories like [26]: engaged/disengaged, frustrated/content, bored/relaxed/under pressure, over-/under-challenged, etc. Using multimodality and fusion [27], [28], high detection rates, robustness and reliability will be reached. The investigation is clustered into a) the dynamic detection and recognition of the environmental situation, intention and emotion of the user, b) modeling aspects and c) interpretation and representation of the overall situation. The need for including information about the emotional state of users into the functionality of a cognitive technical system, results from the neuro-biological fact, that a purely cognitive analysis of human–computer interaction falls short for many areas of human information processing – especially if cognitive technical systems are taking part in social interactions, and when it comes to setting priorities and making decisions. Details of the design of interaction most sensitively account for the success of the sytem-user dialog: In a functional brain imaging study the SFB/TRR 62 observed that an unexpected delay of feedback has a strong effect on brain activation, mainly observed in brain regions known to be involved in attention and action control. This suggests that additional neural resources are needed in such potentially irritating situations. Brain imaging also found that motivational feedback produced a significantly steeper learning curve than feedback with neutral prosody [29]. These findings directly find their way into designing the system's feedback to the user.

Interaction Experiments and Affective Corpora. Because of the importance of emotions in the setting of priorities, in making decisions and controlling actions, the conceptualizing of *Companion*-systems must include situational aspects and emotional processes in dialogs between humans and computers, and it must provide system elements for realization of these effects. Of high importance in this context is the investigation and provision of decision-relevant and actionable corpora within the SFB/TRR 62 from linguistic and non-linguistic human behaviors, which are rarely coded consciously in interpersonal interaction, albeit having great effect on the control of behavior. To that end, we conducted a number of Wizard-of-Oz experiments. The LAST MINUTE experiment allows to investigate interactions of users with a *Companion*–system. It was designed in a way that many aspects of user–companion interaction that are relevant in mundane situations of planning, re-planning and strategy change (e.g. conflicting goals, time pressure, etc.) are experienced by the subjects, with huge number and quality of recorded channels, additional data from psychological questionnaires and semi-structured interviews [30]. In a complimentary Wizard-of- Oz experiment MEMORIZING TASK the emotional load has been induced by a natural language dialog with delay of the commands, non-execution of the command, incorrect speech recognition, offer of technical assistance, lack of technical assistance, and request for termination and positive feedback. This procedure of emotion induction leads the subjects through different locations (octants) in the Valence-Arousal-Dominance (VAD) emotion space.

Four channel peripheral physiological measurements including blood volume pulse (BVP), skin conductance level (SCL) and 2-channel electromyography (EMG) were automatically classified in VAD-space in order to answer the research questions: 1.) to what extent are subject-dependent classifiers of emotion recognition in human computer superior to subject-dependent classifiers and 2.) how robust is the subject-dependent classification transsituational? The study demonstrated that subject-dependent automatical identification of the location in the VAD emotion space outperform significantly with large effect sizes the subject-independent approach in a natural-like human-computer interaction. The data analysis showed that that both EMG signals from corrugators and zygomaticus muscles, HRV and SCL individually differ in their relevance for the classification of emotional responses [31]. However, it remains still unclear whether it will be possible to transsituationally extract stable individual-specific features in different contexts. This may become more possible with sufficient individual–specific information through multimodal assessment with speech prosody, facial behavior and semantic data [27].

Signal Processing for Assessing Situations. In speech, besides sub-symbolic features, also paralinguistic (laughter etc.) and semantic cues play an important role for emotion-expressions. Different emotional analyses tools were applied on different naturalistic corpora, either available or created within our project [32], [33].

In gesture recognition, dynamic (i.e. movement of the hands) and static gestures (postures) are classified [34], taking signs of the American Sign Language (ASL), with recognition rate 94%-99%. For the recognition of dynamic gestures a hidden-markov-model based approach was chosen. Both approaches are currently being integrated [35]. A framework for estimating head poses has been developed [36]. Combining audio information and visual information for the classification of emotional states has been perfomed with multiple features and classifiers [37] on the audio/visual emotion challenge data sets (among top 3 performers, [38]).

Localizing and tracking the involved person(s) is another important issue. Integrating the dependencies among the objects during occlusions is achieved using random finite sets [39].

Some core computational mechanisms of extracting and analyzing nonverbal and visual signals are presented, enabling virtual agents to create socially competent response behaviors. This contributes to installling the basis of social signal processing in companions with human-like abilities [40].

3 Operating Modes of a Companion System

Figure 4 shows the main operational units of a *Companion*-system. A user interacts with a *Companion*-system in a variety of ways and expresses his explicit and implicit requirements of the system usually by multiple, simultaneously

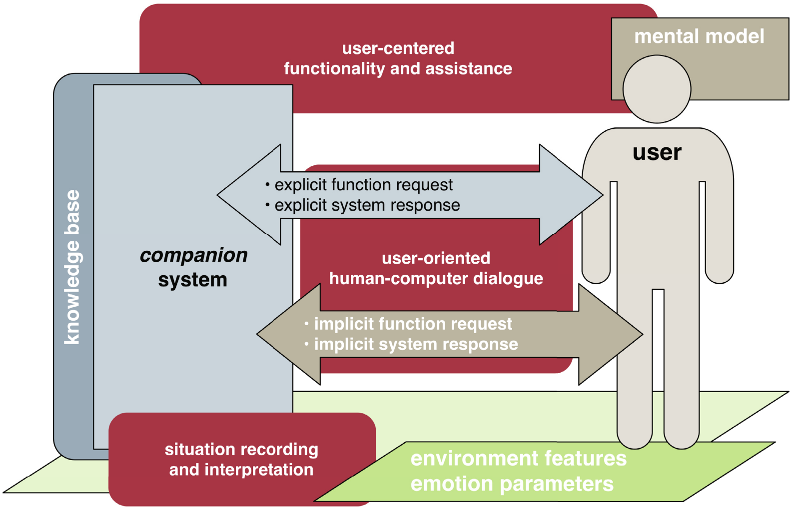

Fig. 4. Operational units of a *Companion*-system

acted, and observable actions. User and system are embedded in an environment that influences both the actions of the user, as well as their observability. A *Companion*-system provides several functions to recognize the intentions of the user, to respond appropriately, and to meet his explicit and implicit requirements. Statements of the user are first recognized as a sequence of observations in different modalities and components, and then classified using operational units for the analysis of language, facial expressions and gestures as well as psychobiological features. The recognition and the assessment of the environment is performed likewise, on the basis of sensory features of the environmental situation. These perceptive features are fused into a sub-symbolic representation of the overall state, representing the emotional state of the user as well as the current environmental situation. The transformation of sub-symbolic representation of the total state into a symbolic state description takes place under inclusion of a stored knowledge model. The symbolic state description provides the basis for intention recognition, and it is utilized for the control of planning and interaction components as well as for dialog control. To realize user-centric functionality and assistance, planning components, based on the current knowledge model, generate action plans and recommendations, and conduct necessary adjustments to the action plans already in progress. The dialog between users and system is performed by components of multimodal interaction. They recognize user actions which are correlated to explicit functional requirements of the *Companion*-system, and which are carried out on different input channels. The associated changes in the state of the application and in the overall situation then result in corresponding system responses. In addition, components of multimodal interaction can realize the output of information to the user, where they use various devices and forms of presentation.

4 Application Perspectives

A *companion technology for cognitive technical systems* is of high relevance for a wide range of applications. Prototypical examples are given below for two application areas.

4.1 Individualized Personal Assistance

Technical solutions for personal assistance systems exist in multitude. A grounded design formalism for such systems, however, is still in research progress [41]. The *Companion*-technology enables the development of a completely new type of personal assistance schemes which are considered reliable companions of their users in carrying out daily tasks and projects in private and professional life. Independent of the location of the user, these assistants are always available, they manage the user's current tasks, they take into account differently prioritized goals, and they support the user in the execution of appropriate actions. The assistants are not only able to react to deviations from planned practices or expected situations in a dynamic and flexible way, but they also independently develop alternative approaches which they pro-actively propose, predicting the consequences. They are familiar with and take into account personal preferences and priorities, they dynamically capture the current environmental situation, as well as the emotional state and the cognitive load of the user, and they accordingly adapt their support services and their communication patterns. They interact with humans, they cooperatively reach solutions, and they may include or opportunistically use specific external services by interacting with third-party systems. The application potential of such assistance systems includes, besides general organizational assistance in professional and private life, especially the support of elder people in their home environment, for which a number of ambient intelligence support scenarios have been identified [42]. In this application, besides assistance in the operation of technical devices or services and personalized support - such as the planning and execution of the daily routine -, even some monitoring functions which can prevent hazards by early detection and if necessary, by requesting assistance from outside, play a central role. The aspects of trust and acceptance of *Companion*-systems are of key importance in this context.

4.2 Medical Assistance Systems

Due to the constant growth of chronic diseases, in the future more and more patients will have to be continuously and individually motivated, supported and guided in the execution of treatment plans, rehabilitation and support measures especially in neurology, geriatrics and pain therapy. This has been clearly stated and identified for various countries by the OECD [43]. Consideration of emotional parameters of patient and therapist is of highest significance for compliance. *Companion*-systems can be utilized here for individualized, interactive patient information, education and guidance. Interactive information portals designed to cooperate with the patient can then, for example, be configured in such a way that, by individualization regarding the cognitive and perceptual abilities of the individual, a better acceptance of the therapeutic suggestions and actions is achieved. Also conversational medicine (psychotherapy, psychosomatic medicine and psychiatry, rehabilitation psychology), which is already heavily based on linguistic communication, increasingly uses information technologies to support their therapies [44], which can benefit greatly from the concepts of individuality, adaptability and trustworthiness. Increasingly important, and well advanced in many countries, is tele-medical care. The treatment of chronically ill patients, old patients, rehabilitation patients and patients in special situations (communication with aircraft, ship and spacecraft crews during the illness of a passenger, assistance of medical personnel in crisis missions, etc.) can be supported by *Companion*-systems to a considerable extent. In connection with medical applications, which increasingly assume an active cooperation of the patient, trustworthiness and acceptance of the systems is of substantial importance. Optimal compliance also requires that the patient experiences the system as individually tailored to his needs, adaptable, universally available and empathic, and that on this basis the patient confidentially interacts with the system.

5 Outlook

Detailed information on subprojects of the SFB/TRR 62 as well as recent publications and research results are available at http://www.sfb-trr-62.de/.

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