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The ROBOCARE Assistive Home Robot: Environment, Features and Evaluation

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The ROBOCARE Technical Reports

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The RoboCare Assistive Home Robot: Environment, Features and Evaluation

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Abstract

This paper describes results from the RoboCare project, whose aim is to create assistive intelligent environments for older people. The specific goal of the project has been to synthesize a multi-agent system in which robotic, software and sensory services are integrated to offer cognitive support to the older user at home. The paper describes the technology that has been integrated to create an empowered robot that assists the user in day-to-day activities. After providing some details on the implementation of the integrated system, the paper describes results from a controlled experimentation with human users. The analysis is aimed at understanding the perception of potential users with respect to the services that are currently supported by the assisted environment.

1 Toward "Robotically Rich" Assistive Environments

The use of intelligent technology for supporting elderly people at home has been addressed in various research projects in the last years, e.g., [29, 28, 17, 30]. Recently, increasing attention is being given to Cognitive Support Systems. As an example, the Calo project [24, 23] has as its primary goal the development of cognitive systems which are able to reason and learn from experience, respond robustly to contingencies, and which can be told what to do and explain what they are doing.

The state-of-the-art in robotics allows now an increasing emphasis on human-robot interaction in general and on *social assistive robotics* in particular. The emphasis in the latter is to support human users through social rather than physical interaction [12].

RoboCare shares several of the challenges with the above mentioned projects. Indeed RoboCare's main motivations can be summarized as follows:

> "The objective of this project is to build a distributed multi-agent system which provides assistance services for elderly users at home. The agents are a highly heterogeneous collection of fixed and mobile robotic, sensory and problem solving components. The project is centered on obtaining a virtual community of human and artificial agents who cooperate in the continuous management of an enclosed environment."

The project has involved research groups with different backgrounds with the goal of investigating how state of the art AI and robotics techniques can be combined to create new domestic services for elderly people [9, 1]. The project has produced a prototype of integrated home environment, called RDE (RoboCare Domestic Environment), composed of a robotic interactive agent, some sensors for continuous monitoring, and additional intelligent systems that store and reason upon knowledge about the assisted elder's scheduled activities. A multi-agent coordination algorithm guarantees the coherence of the behavior of the whole environment. This provides a functional cohesive which invokes the smart home's services so as to preserve safeness of the person and provide suggestions. The RDE includes a mobile robotic platform with interaction capabilities. This robot provides an interface between the RDE and the user: indeed, the entire smart home is accessible to the user in the form of an assistive robotic companion.

In the spirit described in [12] the RDE is an example of Social Assistive Robot, a concept which can be distinguished from Social Interactive Robot [13] because its main task is to monitor and assist the elder user rather than simply interacting with him/her. Since its beginning, RoboCare has raised numerous challenges. In particular one, also reported in [35], has been paramount in our work: "what are the circumstances in which people accept an assistive robot in their environment?". Other important questions we have strived to answer (or at least investigated) are "how should an elder user communicate with a robot?", "should the robot look like a human being?", and, last but not least, "are robots useful in the domestic environment?".

Our project started with a preliminary study [33, 32, 15] aimed at providing a "best guess" for some of the above questions. This paper comes after three years of development in which we have attempted to realize a prototypical domestic environment equipped with an assistive robot. The aim of the paper is to describe an *a-posteriori* evaluation of the validity of our choices. In particular, we present experiments aimed at understanding the real perception of older people towards the assistance that this robot is able to offer at the moment.

Related Work.

Human-robot interaction for socially assistive applications is an emerging research topic that involves several heterogeneous disciplines [12, 35]. The increasing number of specialized interdisciplinary events dedicated to this topic proves the importance of integrating different experiences and competencies to succeed. One of the most important aspects of social assistive robots consists in social interaction between human users and robotic agents. In [31] it is highlighted how observation and behavioral analysis of human-robot social interaction in real environments is necessary in order to take into consideration all the divergent factors pertaining to the design of social robots. In particular, in this work the use of observational studies of human-robot social interaction in open, human-inhabited environments has been proposed as a method to provide useful guidance to designers of social robots as well as to improve the evaluation of their interactive capabilities.

Other works have investigated the psychological, social and physiological effects of robots on humans for therapeutic purposes. In [36], authors have applied the mental commit robots to assist activities of elderly people at a day-service center. In [10], authors discuss the area of autism and how mobile robots can play a therapeutic role in the rehabilitation of children with autism. Different work has stressed the distinction between hands-on vs. hands-off assistive tasks. Being interested in the latter, it is worth mentioning the work on assisting older people in a healthcare institution [29, 28], and several works on assisting rehabilitation tasks for cardiac patients, i.e., [11].

Within the RoboCare project previous research [32, 33] showed how people have difficulties in depicting a realistic representation of what an assistive robot can actually do in the domestic environment, showing a strong tendency to overestimate "manipulative" abilities and underestimate robots' cognitive capabilities. The present work further contributes in this direction. In particular our previous study on human-robot interaction within RoboCare focused on users' attitudes toward an imaginary robotic agent. The present study, on the other hand, is carried out within an actual RDE, which allowed us to develop more realistic situations where the RoboCare robotic platform acts as a cognitive assistant and helps users in cognitive tasks.

Plan of the Paper.

The paper starts with a technical description of the RoboCare Domestic Environment which includes the robot, the intelligent analysis performed on the vision sensors, the temporal reasoning service based on scheduling technology and the coordination algorithm which guarantees the functional coherence of the multi-agent environment. Section 3 presents the experimental set up and the result obtained with elder users, while Section 4 analyzes the obtained results. A concluding section ends the paper.

2 The RoboCare Experience: Heterogeneous Ingredients in a Smart Home

The RDE is aimed at demonstrating instances in which the coordinated operation of multiple household agents can provide complex support services for the elder user. For instance, suppose the assisted person is in an abnormal posture-location state (e.g., lying down in the kitchen). The intelligent home should recognize this situation and react to the contingency by dispatching the robot to the person's location. The robot should then ask if all is well, and if necessary sound an alarm.

Proactive system intervention may also be triggered by complex symbolic reasoning. A meaningful example: the smart environment detects that the time bounds within which to take a medication are jeopardized by an unusual activity pattern (e.g., the assisted person starts to have lunch very late in the afternoon); as a consequence, the system should verbally alert the assisted person of the possible future inconsistency. An even more advanced form of reasoning-driven interaction could be the following: the assisted person asks the intelligent environment (e.g., verbally) whether he/she should take a walk now or wait till after dinner; the request is forwarded to a specialized reasoner which propagates the two scenarios (walk now or walk after dinner) in its temporal representation of the daily schedule, and the result of this deduction is relayed to the assisted in the form of verbal advice (e.g., "if you take a walk now, you will not be able to start dinner before 10:00 pm, and this is in contrast with a medication constraint").

The objective of our prototype is to show how a collection of service-providing and very diverse agents (namely, in our specific case, artificial reasoners, robots and smart sensors) can be integrated into one functionally coherent system which provides more added value than the sum of its parts. The type of elementary services deployed in the RDE mirrors the domotic components that will be available on the market in the near future. In this context, a special focus of RoboCare has been to explore the role of an embodied agent which provides an interface between the assisted person and his or her smart home environment. Our integration effort has yielded an integrated environment which interacts with the assisted person through what we have called a *robotic mediator*. The base on top of which the robotic mediator is built consists in a Pioneer platform. The mobile platform is equipped with additional sensors, namely a laser range finder, a stereo camera and an omni-directional camera, as well as additional computational resources consisting in two laptops, one for on-board sensor processing and navigation and one for human-robot interaction. The robot is endowed with verbal user interaction skills: speech recognition is achieved with the Sonic speech recognition system (University of Colorado)[1], while speech synthesis is driven by a simple text-to-speech system.

We start the description of the robotic mediator from its mobility subsystem, i.e., the specific solutions we have adopted to obtain a robot companion which can robustly and safely navigate in the domestic environment. We then briefly discuss the peripheral components of the RDE, namely the sensory systems which we have deployed (person local-

[1] For details, see `cslr.colorado.edu/beginweb/speech_recognition/sonic.html`.

ization/tracking and posture recognition) as well as a software agent which provides the RDE with temporal reasoning capabilities. As the RDE is achieved by integrating diverse technology, we also briefly describe the overall coordination schema which provides service concertation.

2.1 The Robotic Platform

In the following paragraphs we briefly describe the functionalities of navigation, path planning, mapping and localization providing the basis for added-value services which require physical presence. Since the overall aim of this paper is to describe the role of the robotic mediator within the assistive system, we omit some details concerning the aspects related to the mobile platform. These aspects are nonetheless given a high-level description, and pointers to specific technical results in localization and artificial vision are given.

A significant part of our research in the early stages of the RoboCare project was dedicated to obtaining a reliable and robust mobility subsystem for the robotic mediator. The results of this research are a set of key mobility services consisting in primitives which can be invoked to make the robot reach any position in the domestic environment.

Localization and mapping is the primary requirement for implementing a robust mobile platform in the domestic environment. Underlying the mobility services is a Sampling Importance Resampling (SIR) particle filtering algorithm, which is extensively described in [16]. In particular, SIR is particularly suited for the domestic scenario, in which the map of the environment may change in an unpredictable manner. Indeed, the approach allows to take into account the position of chairs, tables, sofas, or any other object whose position is likely to change over time.

Given the capability of localizing itself in the environment, the mobile platform must provide a "goto-place" service which can be invoked in order to make the robot move robustly from one position in the environment to the other. In particular, the RoboCare robotic platform provides two levels of mobility services: a `goto-XY(x, y)` function on one hand, which triggers the robot to reach a certain (x, y) position in the environment, and a `goto-place(dest)` primitive through which the robot can be sent to a particular known destination (such as "the sofa", or "the lamp"). Clearly, the latter functionality is at a higher level of abstraction than the former, and in our system consists in a naming scheme which associates names to coordinate pairs. Therefore, invoking the `goto-place()` command will result in a look-up in the location database followed by the appropriate invocation of the `goto-XY()` functionality. Since the core of the mobility infrastructure comes into play at the `goto-XY()` invocation level, we here briefly describe the topological path planning algorithm underlying this primitive.

Autonomously navigating towards a given coordinate pair in the domestic setting is not a trivial problem. It poses both general problems pertaining autonomous navigation, as well as problems which are unique to the domestic environment. Using complete algorithms to find the topology of the environment (e.g., Voronoi diagrams) is very expensive and, since we have a different map at each cycle, a probabilistic approach is more convenient for the topological path-planner.

The most widely used approach that builds a graph representing a roadmap of the environment is the Probabilistic RoadMap (PRM) [19] algorithm. This algorithm works by picking random positions in the configuration space and trying to connect them with a fast local planner. The problem with this algorithm is that it expects as input a map that does not change over time. This requirement cannot be upheld in the domestic environment, where some furniture is frequently moved (e.g., chairs, small tables, etc.) and new objects can clutter the environment semi-permanently.

In order to overcome this limitation, we employ an algorithm which combines PRM with Growing Neural Gas (GNG) [14]. GNG is a neural network with unsupervised learning, used to reduce the dimensionality of the input space. In this kind of network, nodes represent symbols and edges represent semantic connections between them; the Hebbian learning rule is used in many approaches to update nodes and create edges between them. Given a system which has a finite set of outputs, applying the Hebbian rule allows for modifying the network in order to strengthen the output in response to the input. Otherwise, given two outputs that are correlated to a given input, it is used to strengthen their correlation. For our concerns, the nodes (symbols) represent locations and the edges the possibility to go from one location to another. In this sense, we can use, together with the Hebbian learning rule, a simple visibility check in order to create a link between two nodes, as PRM does. GNG cannot be straightforwardly used in a robot motion problem, because the topological information is valid only when the graph has reached a state of equilibrium.

The Dynamic Probabilistic Topological Map.

The algorithm we use for domestic navigation is known as Dynamic Probabilistic Topological Map (DPTM) [6]. It successfully combines PRM and GNG, taking into account the characteristics of the considered environment. There are two main issues in this kind of algorithm: (1) when to add a new node (i.e., a new milestone in the topological representation of the environment), and (2) when to add a new edge between two nodes (i.e., when to consider two nodes as part of a path). Intuitively, the approach implemented in DPTM can be described as follows.

Adding new nodes. Since only those nodes that are needed to represent the topology of the environment have to be added, the algorithm does not add a new milestone each time a new position is presented to the network, but only if (1) the position cannot see any other node already in the network, and (2) the introduction of a new node makes it possible to connect two nodes that were already present in the network. If a node does not have to be added, the Hebbian learning rule can be used in order to reduce the error distortion in the set of positions represented by the node. This allows to increment the chance of connecting it with other nodes (as experimented in [38]). The second criterion is similar to that used in [34], but since in this case a node could be a connection between two nodes, there is no fixed role.

Adding new edges. Concerning the edges, a node is not connected with all its neighbors, as this would be a redundant representation of the environment. Instead, a Hebbian learning rule is used to connect the two nodes nearest to the current input position. Clearly, also the two edges that connect the new position to two nodes that cannot see each other are added.

The low number of nodes in the topological map make it easy to move them to different positions as topology changes. It thus becomes easy to check at each cycle if some edges are no longer valid and can be removed. Overall, DPTM has a number of significant advantages compared with PRM and GNG (see [6]). Specifically, it allows to represent the topology of the environment with merely 1% of the nodes required by PRM. Moreover, the density of nodes is a function of the complexity of each portion of the map, and not uniform (as is the case in GNG) thus providing for a good trade-off between accuracy and relevance of the representation. Moreover, using a DPTM we can extract the topology information of the environment, i.e., each path in the environment can be represented on the DPTM, while the PRM algorithm tries to achieve only the connectivity, eventually losing in the graph some connection existent in the environment. This means that with DPTM we can use some method in order to find the optimal path between two positions, while in general with PRM this cannot be done.

Overall, DPTM easily adapts to the topological changes of the environment, making it useful in an environment whose map can change often and without notice (as is the case in the domestic environment, where the user can move objects and clutter the map relatively often). Indeed, DPTM is suited for even more dynamic environments, e.g, where the map is built incrementally during exploration such as the rescue scenario.

2.2 Environmental Sensors

A major objective of the RoboCare project was the integration of different intelligent components that

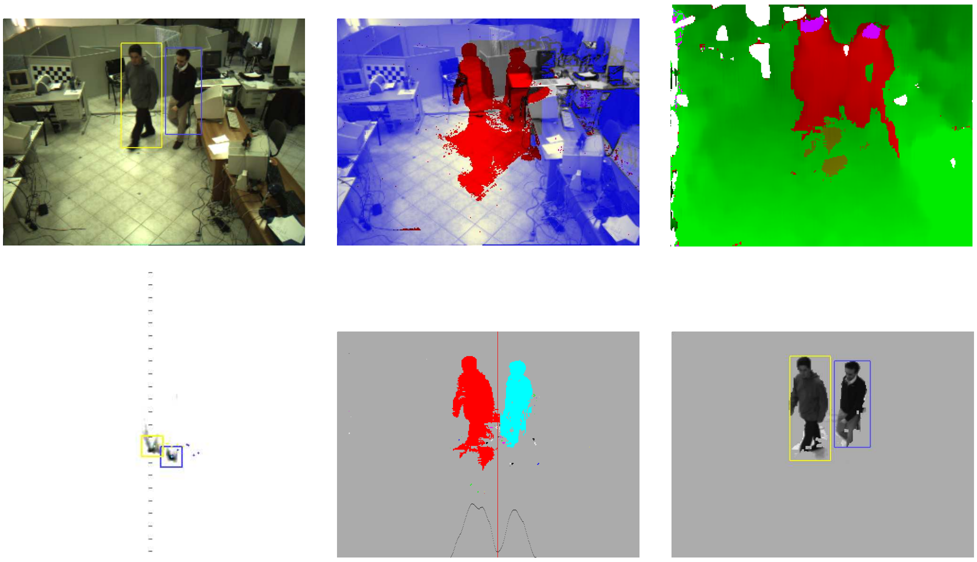

Figure 1: The phases of the PLT service (from left to right, top to bottom): original image, intensity foreground, disparity foreground, plan-view, foreground segmentation, and person segmentation.

are deployed not only on board of a mobile robot, but also as "intelligent" sensors in the environment. In particular, we have developed a People Localization and Tracking service[2] (PLT) based on a stereo vision sensor, which provides the means to locate the assisted person and other people in the environment. This environmental sensor was deployed at RoboCup@Home 2006 in Bremen in the form of an "intelligent coat-hanger", demonstrating easy setup and general applicability of vision-based systems for in-door applications. The system is scalable as multiple cameras can be used to improve area coverage and precision. In addition, vision-based posture recognition can be cascaded to the PLT computation in order to provide further information on what the assisted person is doing.

Our stereo-vision based tracking system is composed of three fundamental modules: (1) background modelling, background subtraction and foreground segmentation, that are used to detect foreground people and objects to be tracked; (2) plan-view analysis, that is used to refine foreground segmentation and to compute observations for tracking; (3) tracking, that tracks observations over time maintaining association between tracks and tracked people (or objects).

The PLT service is effectively capable of tracking the position of a human being within a domestic environment. In addition, the system is resilient to changes in the lighting conditions of the environment, thus enabling portability and easy setup (as demonstrated at the RoboCup@Home competition). This characteristic is particularly useful in domestic environments, where strong differences may occur due to artificial and natural lighting conditions. The key solutions which have made these features possible are:

1. The background model, which is a composition of intensity, disparity and edge information; it uses a *learning factor* that varies over time and is different for each pixel in order to adaptively and selectively update the model; moreover, it uses a new notion of *activity* based on edge variations.

2. Plan-view projection computes *height maps*, which are used to detect people in the environment and refine foreground segmentation in case

[2]See `http://www.dis.uniroma1.it/~iocchi/PLT` for an overview.

of partial occlusions.

3. *Plan-view positions* and *appearance models* are integrated in the tracker and an optimization problem is solved in order to determine the best matching between the observations and the current status of the tracker.

The output of these three phases of the computation is depicted in figure 2.2.

In addition to the PLT service, the system also provides a People Posture Recognition (PPR) service. Specifically, this module is cascaded to the PLT module, as its input is the person-blob obtained by the PLT algorithm. In addition, the service relies on a 3D human body model which has been carefully chosen by considering the quality of data available from the segmentation steps. In our application the input data are not sufficient to cope with hands and arm movement. This is because arms are often missed by the segmentation process, and noises may appear as arms. Without taking into account arms and hands in the model, it is not possible to retrieve information about hand gestures, but is still possible to detect most of the information that allows to distinguish among the principal postures, such as *STANDING*, *SITTING*, *BENT*, *KNEELING*, and *LAYING*. Our application is mainly interested in classifying these main postures and thus we adopted a model that does not contain explicitly arms and hands.

A detailed description of the PLT and PPR services is outside the scope of this paper, and the interested reader is referred to [2, 8] for further descriptions of the technology underlying the PLT and PPR services. Nevertheless, we should underscore that these services are key enabling factors for the sophisticated cognitive support services provided by the smart home. Constant tracking and posture recognition allows to deduce the state of the assisted person, and is therefore responsible for activity recognition. As we briefly explain in the next sections, recognized activities are propagated within a temporal representation of the assisted person's daily schedule, which in turn triggers the proactive behavior of the robotic mediator (in the form of suggestions, warnings, and so on).

2.3 Intelligent Software Services

The sensory capabilities provided by the PLT and PPR services are employed in RoboCare to monitor the user's daily activities. While the above services cannot provide an "all-knowing" smart home, they are sufficient to recognize key activities that are carried out by the assisted person during the day. Activity recognition thus provides a means to assess whether the assisted person is following given behavioral constraints (such as taking the right pills at the right time, eating regularly, and so on). In order to provide the system with the capability to perform these deductions, we have developed a schedule management environment called T-Rex (Tool for schedule Representation and eXecution [26]), through which it is possible to represent of a set of activities and their quantitative temporal connections (i.e., a schedule of activities that the user is expected to carry out). The broad idea is to allow the specification and then the execution monitoring of a set of activities that the person usually performs or needs to perform due to prescription (on suggestion from his personal doctor for example).

T-Rex integrates a constraint-based scheduler [7] with additional features for knowledge engineering, in particular for problem modeling. Particular attention has been given to the definition of "user-oriented terminologies" in order to easily synthesize both the basic elements of a target domain as well as different problem instances in the particular domain (i.e., in the form of activities and constraints among activities). For example, in the RoboCare context, T-Rex allows to define "home domain activities" like *breakfast*, *lunch*, *go-for-walk*, and also temporal/causal links among activities like *meal-bound-medication* to express rules like "aspirin cannot be taken before eating". Through this high level language an external user (a doctor, a relative of the assisted person, etc.) may define a network of activities, a *schedule*, that the observed person is supposed to carry out in the home environment during the day. This schedule is dispatched for execution and monitored using the underlying schedule execution technology. Information coming from the sensors is used for maintaining an updated representation of what is really happening in the environment. Even if human activity recognition[3] is outside the scope of the project, it is worth highlighting how the sequence of observations from the artificial vision sensors allows to follow the evolution of the activities of the observed person (e.g., if and when she took a pill, when she had lunch, etc.). Based on the synthesis of these observations, the system is able to generate a report for the external users that underscores when the person's activities have been performed within "reasonable" temporal boundaries or when important anomalies or even violations on their execution have been detected [1]. In this light, the RDE constitutes a basic example of home *activity monitor* grounded on scheduling technology.

Notice that, on its own, the domestic activity monitor acts as a "silent observer" and does not take initiative with respect to the elder person in any way. In order to close the loop, we need to show how its indications are employed to trigger system initiatives through the robotic mediator. This is achieved through a distributed coordination infrastructure. A brief description of how this works is given in the following section.

Overall, the activity monitor is tightly connected to the interaction between the robotic mediator and the assisted person. Its temporal deductions can give rise to instances of communication with the elder user: if the system recognizes that some temporal constraint is violated, such as taking medication on an empty stomach, the robot will pro-actively intervene by navigating towards the user and communicating a warning message. Also, the temporal reasoning services are exploited when the user spontaneously asks the robot about activity-related concepts, such as "have I taken my pills?" or "when should I start cooking?".

Finally, we should mention that significant efforts have gone into establishing a scheme for deducing verbal messages that are as convincing as possible. In practise, when a temporal constraint is violated, the activity monitor signals the nature of the violation in terms of the two activities involved in the violated constraint. This information is sufficient to distinguish classes of warnings (e.g., something has occurred to early/late, the user is trying to perform activity A before activity B, etc.). These classes correspond to general purpose phrases, and the occurrence of a specific constraint violation thus results in a human intelligible phrase such as "Jane, you should not take your pills on an empty stomach – how about some breakfast?".

2.4 Multi Agent Coordination Infrastructure

RoboCare requires the combination of various intelligent tools to ensure a comprehensive behavior of the enhanced physical environment. Our goal is to achieve an environment which acts as a *proactive assistant for daily activity monitoring.* This section explains how heterogeneity is kept under control by synthesizing a coordinated behavior.

Coordination of multiple services is achieved by solving a Multi-Agent Coordination problem. This problem is cast as a Distributed Constraint Optimization Problem (DCOP), and solved by Adopt-N [25], an extension of the Adopt (Asynchronous Distributed Optimization) algorithm [22] for dealing with n-ary constraints. Figure 2 gives an intuition of the approach[4]. Let $Application_i$ be the generic intelligent subsystem that is to be integrated in the overall multi-agent system, and Var_j one out of a set $\mathcal{V}$ of variables in terms of which the coordination problem is defined. Each variable has an associated domain of Values D_j. Variables are bound by constraints like in regular Constraint Satisfaction Problems (CSP). Conversely, while constraints in CSP evaluate to *satisfied* or *unsatisfied*, in the optimization case constraints evaluate to costs. Constraints may involve an arbitrary subset of the variables (n-ary constraints): a constraint among the set $C \subset \mathcal{V}$ of k variables is expressed as a function in the form $f_C : D_1 \times \ldots \times D_k \rightarrow \mathbb{N}$. For instance, a constraint involving the three variables $\{Var_1, Var_3, Var_7\}$ may prescribe that the cost of a particular assignment of values to these variables

[3]There is plenty of recent research on activity recognition with sensors, e.g., [27], that could be potentially impact on this class of applications.

[4] Further details are given in [8].

amounts to c, e.g., $f_{Var_1,Var_3,Var_7}(0, 3, 1) = c$. The objective of a constraint optimization algorithm is to calculate an assignment $\mathcal{A}$ of values to variables while minimizing the cost of the assignment $\sum_{C \in \mathcal{C}} f_C(\mathcal{A})$, where each f_C is of arity $|C|$.

In RoboCare, the valued constraints are decided in order to orient the solution of the DCOP toward preferred world situations (broadly speaking those situations in which the person is maximally helped by the intelligent system). The system is composed of a number of heterogeneous applications: (a) the T-Rex activity monitor (described in the previous section), (b) the dialogue manager plus the speech I/O modules, (c) the mobile robotic platform, (d) one application for each of the cameras, each of them with the appropriate software for PLT and PPR.

Figure 2: DCOP to maintain distributed coherence.

Each application manages one or more of the variables which are part of the DCOP. A variable may represent (a part of) the input to an application, its output, or both (see the dashed lines in Figure 2 as an example). When the DCOP resolution algorithm (Adopt-N) is called into play, the values of the application-output variables are taken into account in the distributed resolution. When resolution reaches a fixed-point, the input variables will reflect an updated input for the applications. The correspondence between the applications' output at the i-th iteration and their input at iteration $i+1$ is a result of the propagation rules specified in the DCOP. Overall the decisions of the applications constitute the input for the subsequent iteration of the cycle ⟨*DCOP-resolution; read-variable; application-decision; write-variable*⟩.

It is worth underscoring that the multi-agent solution based on DCOP guarantees continuous control over the whole environment. Additionally, the value functions f_C allow to bias the produced solution towards aggregate behavior which is helpful for the assisted person.

3 Experiments with Elder Users

The RDE's fundamental building blocks described in the previous sections are the result of a multidisciplinary research and development effort, combining robotics, artificial vision, automated scheduling and distributed constraint reasoning. In all these fields, research has been driven by the specific requirements of the assistive environment scenario. Our aim in the remainder of this article is to provide an evaluation of the validity of our choices. In particular, we present experiments aimed at understanding the real perception of older people towards the assistance that the robot (and thus the assistive environment as a whole) is able to offer at the moment.

Another result which has driven our development effort is an *a-priori* evaluation of laypeople's perception of assistive robots. Specifically, the study was based on an imaginary assistive robot, and was performed before the development of the RDE. This pilot study was aimed at drawing some preliminary desiderata and requirements for the RDE.

3.1 Preliminary Evaluation of Assistive Robots

The pilot study, reported in [33], was aimed at analyzing laypeople's representations of domestic robots with respect to a variety of topics: the respondants' expectations with respect to the robot's capabilities to perform different everyday activities at home; their emotional response to a domestic robot; the image of the robot, referring to shape, size, color, cover material, speed; preferences and expectancies about the robot's personification (given name, etc.) and the modalities of human-robot communication and interaction.

Results showed that people have difficulties in depicting a realistic representation of what a domestic robot can actually do in the domestic environment, showing a strong tendency to overestimate "manipulative" abilities and underestimate robots' cognitive capabilities. This is presumably the consequence of the most widespread source of information about robots, namely science fiction: a domestic robot is still too far away from the everyday life experience of laypeople.

In addition, people at different stages of their lifespan showed very divergent opinions and preferences about the robot's appearance and interaction modalities. In particular, older people emerged as a quite homogeneous group in indicating a preference for a small device, with a standard aspect and no sign of personalization, not autonomously free to move in the domestic environment and simply responding to tasks to be performed — a mere task executor, hardly resembling a human being, which has to intrude as less as possible in personal and domestic life. In fact, while its practical utility was recognized, the robot emerged as a potential source of danger and discomfort in private life, and the idea of a non-autonomous device which does not show human features seemed to be a way to ward off their anxiety. Another issue to be addressed has to do with the context in which the robot is expected to operate. The use of new technologies and domestic robots in the home environment is not only a matter of general human-technology interaction, but is also associated with the specific sphere of human life in which assistance is needed [15]. Elderly people showed a rather positive attitude towards a technological modification in the domestic environment, yet the inclination to use technological devices is strongly associated to the problem they have to cope with. In some situations, a technological aid seemed to be unrealistic, or unpractical, or it would have better been replaced by a more common alternative. In other ones, concerning health and personal/environmental safeness above all, it emerged as a suitable solution to cope with losses imposed by ageing. As a consequence, the possibility of identifying everyday activities for which the acceptability of a technological help is likely to be pervasive is undoubtedly an interesting research issue.

3.2 The Present Study

The pilot study mentioned above focused on the study of users' attitudes toward a purely imaginary robotic agent, with no specific abilities and not operating in a real domestic environment. For this reason, differences in users' reactions could have been related to both diverse knowledge and bias toward technologies. Nevertheless, these preliminary results were important for driving development in RoboCare.

The final prototype we have described in this paper allows us overcome the previous limitation. The evaluation of a tangible robot – which is the result of three years of development – allows us to eliminate the pre-concepts and other biases. Performing the evaluation on the RDE prototype allows us to draw specific conclusions on the RDE, but also to concretely answer some general questions relative to the challenges of assistive technology for elderly people. This analysis is in line with current recommendations for the evaluation of complex assistive technology. For instance, it is recognized in [18] that human-robot interaction is to be evaluated on socio-culturally constituted activities outside the design laboratory. In this light, the aim of our research is to analyze the potential reactions of final users to real life interactions between elderly people and an assistive robot.

The present analysis considered eight different scenarios, which were meant to be representative of daily situations in which elderly people may be involved. The situations were selected with reference to previous research on this topic [15], ranging from the most emotionally involving to less critical and emotionally neutral, with the aim of exploring elderly people's evaluations of the potential role of a domestic robot as a useful support to ageing people. Specifically, the study focuses on three aspects. First, we perform an evaluation of how meaningful each scenario is with respect to the respondents' every day life. This allows us to understand how useful state-of-the-art assistive technology can be in real situations. Moreover, it provides a precious indication as to whether we are employing this technology to solve real needs. Finally, assessing scenario meaningfulness is aimed at understanding the weight we should give to the user's evaluations in each scenario.

Second, we focus on the respondents assessment of our robotic mediator. The RoboCare project has allowed us to perform an evaluation on a real platform within a fully implemented domestic assistive environment. As a consequence, the evaluation is presumably not affected by prejudice and/or knowledge in the area of robotic systems. The analysis focuses on aspects related to the physical aspect of the robot, its interaction capabilities, and in general its suitability in the domestic context (e.g., size, mobility, integration with the environment). In addition, the usefulness of the system is evaluated in the different scenarios.

Finally, we observe user preferences with respect to the robot's resemblance to a human being. Although our robot is not anthropomorphic, it is possible to deploy it in two slightly different versions: one in which the robot has a 3D facial representation (whose lip movement is synchronized with the speech synthesizer), and one without a facial representation. These variants were used to toggle the variable "Resemblance to human beings", which is emerging as a key component in elderly people's representation of domestic robots [33].

A final aim was to analyze the influence of age, familiarity with technologies and perceived health conditions on the evaluation of the robotic agent, being all of these variables strongly related to the possibility of elderly people to adopt a technological solution in the management of everyday difficulties [15].

Materials.

Eight short movies (ranging from about 30 seconds to little more than one minute) were developed showing potential interaction scenarios between an elderly person and the RDE's robotic agent in a real domestic environment. The same scenarios were shot with an actor and an actress. The features of the robotic agent were manipulated according to two different experimental conditions: in the first condition ("Face") a robot showing a human speaking face on a notebook monitor; in the second ("No-face"), a robot with no anthropomorphic characteristic (see Figure 3). The eight scenarios presented everyday life situations in which the robot provides cognitive support to the elderly person. The following topics, referring to critical areas for the elderly, as highlighted by previous research, were considered: (a) management of personal/environmental safety, (b) healthcare, (c) reminding events/deadlines, (d) support to activity planning, (e) suggestions. In the following, the eight scenarios are shortly described.

(a) (b)

Figure 3: The two versions of the robot corresponding to the different experimental conditions.

Scenario 1 ***[Environmental safety]*** *The actor/actress is sitting on the sofa, watching TV. In the meantime, in the kitchen the sauce on the stove is overcooking. The sensors communicate this information to the robot. As a consequence, the robot moves toward the actor/actress and says: "The pot is burning. You should turn it off". The actor/actress immediately goes to the kitchen and turns the stove off.*

Scenario 2 ***[Personal safety]*** *The actor/actress is sitting on the sofa, reading a magazine. Suddenly, he/she feels ill, and loses consciousness (or faints?). The camera recognizes the situation and communicates this information to the robot. The robot approaches the actor/actress and says: "Are you all right?". As it gets no answer, the robot calls the actor's/actress' son at work, who calls the medical emergency. The final scene shows the son and the* *doctor in the living room with the actor/actress, who feels fine.*

Scenario 3 ***[Finding objects]*** *The actor/actress is sitting on the sofa, and takes a magazine to read. Suddenly, he/she realizes that the glasses are not on the table in front of him/her. The actor/actress calls the robot and asks: "Where are my glasses?". The sensors in the rooms search for the glasses, and finally find them in the kitchen. The robot answers: "The glasses are on the table in the kitchen". The actor/actress goes to the kitchen and takes the glasses, then goes back to the sofa and starts reading the magazine.*

Scenario 4 ***[Reminding analyses]*** *The actor/actress is in the kitchen. He/she is about to have breakfast. When he/she puts the pot on the stove to warm up the milk, the robot says: "You cannot have breakfast now. You have an appointment for a medical analysis". The actor/actress answers: "You're right. I had forgotten all about it!".*

Scenario 5 ***[Activity planning]*** *The actor/actress is having a call in the living room. He/she is speaking to the secretary of a clinical center to have an appointment for a medical examination. The secretary proposes an appointment for the next day, with two alternatives: one in the morning, the other in the afternoon. The actor/actress asks the robot for eventual engagements in the following day. The robot answers: "You have another engagement in the morning. In the afternoon, you do not have any appointment". The actor/actress accepts the appointment in the afternoon.*

Scenario 6 ***[Reminding medication]*** *The actor/-actress is sleeping on the sofa, and suddenly wakes up. He/she does not realize what time is it, and thus he/she asks the robot. The robot answers: "It is four o'clock". The actor/actress does not remember whether or not he/she took his/her medicine after lunch, and asks the robot. The robot answers: "Yes, you took it."*

Scenario 7 ***[Suggestions]*** *The actor/actress is watching TV on the sofa. It is five o'clock. The robot enters the living room and says: "You have been spending all the day at home. Why don't you go out and have a walk?". The actor/actress answers: "I really don't feel like it... I think I'll go water the plants in the garden".*

Scenario 8 ***[Reminding events]*** *The actor/actress is having breakfast in the kitchen. The robot reminds him/her: "Today it's your friend Giovanni's birthday. Remember to call him". The actor/actress answers: "You are right. I will do it in a while". Then he/she goes to the living room and calls Giovanni.*

Tools.

A questionnaire was developed for data collection. It consisted of four sections, plus a final part for socio-demographics. The four sections were arranged as follows:

Section 1. Eight fill-in papers, each of them referring to one of the eight scenarios, were presented. For each scenario, questions about the likelihood of the situation for the elderly person, the utility and acceptability of the robot were asked.

Section 2. An attitude scale, consisting of 45 Likert-type items, referring to the physical aspect of the robot, its behavior and communication modalities; the level of integration with the domestic environment; the degree of perceived intrusion/disturbance of the robot in everyday life and routines; the personal advantages and disadvantages of having such a device at home.

Section 3. An emotional scale, consisting of sixteen adjectives through which respondents have to evaluate the possible presence of the robot in their home.

Section 4. Questions about familiarity with new technologies, worries with cognitive impairments related to ageing, and perceived health conditions were asked.

The questionnaire consisted of both multiple-choice and 5-step Likert-type items, to which respondents had to express their level of agreement/disagreement on a scale ranging from 0 ("I totally disagree") to 4 ("I completely agree").

Participants.

Subjects recruited for this exploratory study were forty elderly people (aged 56-88 years; mean age = 70.3 years). Participants were 13 males and 27 females; as for their educational level, 17.9% attended primary school, 43.6% attended middle school, 25.6% attended high school, 12.9% have a degree. Most of them (82.5%) are retired. Before retirement, 22.5% were teachers, 15% were office workers.

Procedure.

Subjects were randomly assigned to one of the two experimental conditions (Face/No-face). The movies were either projected on a notebook monitor, in a face-to-face administration, or on a larger screen, in a small-group administration. All administrations were performed in quiet settings. Two different sequences of presentation of scenarios were used, in order to avoid the potential influence of an order effect of episodes on results. After the vision of each scenario, participants were asked to fill the paper specifically referring to it (Section 1 of the questionnaire). At the end of the whole presentation, subjects were asked to give general evaluations of the robot (Sections 2-4 of the questionnaire), and to fill the final part of the questionnaire, referring to socio-demographics.

3.3 Results

As mentioned, the analysis of the results is aimed at investigating four specific aspects related to the acceptability of a domestic robotic assistant. Specifically, our results are aimed at

- measuring how meaningful each of the eight scenarios is with respect to the respondents' every day life;
- providing a general evaluation of the robotic mediator, as well as a specific evaluation of user preferences in the various scenarios;
- understanding the preferences of elder users with respect to the robot's resemblance to a human being.

Preliminary Analysis.

A preliminary analysis shows that the selection of scenarios was effective in identifying typical everyday situations. Specifically, the analysis reveals that Personal safety ($M = 2.80, sd = .72$), Finding objects ($M = 2.80, sd = .94$), Reminding medication ($M = 2.78, sd = .92$), and Environmental safety ($M = 2.68, sd = .83$) are the most likely situations. The Suggestion scenario ($M = 1.78, sd = 1.19$) was evaluated as somewhat unlikely (see Figure 4).

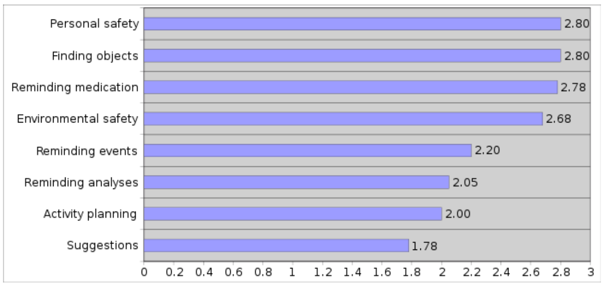

Figure 4: Likelihood of situations.

General evaluation of the robot.

As to the different characteristics of the robot (see Section 2 of the questionnaire), its interaction behavior and communication modalities were on average positively assessed: elderly people like a face-to-face interaction with the robot ($M = 2.60$, $sd = 1.23$) and its pace in the domestic environment ($M = 2.52$, $sd = 1.20$); the speech is appreciated as a way to foster interaction ($M = 3.20$, $sd = .99$), the speed of voice is adequate ($M = 2.67$, $sd = 1.14$) and the robot is easy to understand on the whole ($M = 3.08$, $sd = 1.10$). The robot's integration with the home environment is good: elderly people are positively impressed by its ability to move in the domestic environment ($M = 3.48$, $sd = .75$), and are not afraid of possible damages ($M = 1.60$, $sd = 1.35$), even though a total freedom of movement at home is not completely appreciated ($M = 1.52$, $sd = 1.38$). Elderly people realize a variety of advantages associated with the presence of the robot in the domestic environment: feeling safer for people living alone ($M = 3.23$, $sd = 1.14$), a valid support for cognitive functioning ($M = 3.23$, $sd = .92$) and, in general, in the organization of everyday activities ($M = 2.98$, $sd = 1.03$); on the other hand, some troubles with the management of the device (repairs, etc.) ($M = 2.95$, $sd = 1.11$) and the possible economic costs ($M = 3.25$, $sd = .84$) are expected. Finally, the robot is hardly perceived as a potential source of intrusion/disturbance in their personal life ($M = 1.43$, $sd = 1.39$) and the possibility for it to take decisions autonomously is highly valued ($M = 2.88$, $sd = 1.30$).

Scenario-specific evaluation of the robot.

A global picture of the robotic mediator reveals a rather positive perception, especially when considering the potential advantages in the management of everyday situations. The robot emerged as a very useful device for Personal ($M = 3.10$, $sd = 1.01$) and Environmental safety ($M = 2.83$, $sd = .90$), Reminding medications ($M = 2.68$, $sd = .97$), and Finding objects ($M = 2.63$, $sd = .98$); conversely, not particularly useful in case of Suggestions ($M = 1.85$, $sd = 1.14$) (see Figure 5). In addition to utility, the robot was also indicated as a solution users would accept when difficulties arise, again with specific reference to Personal ($M = 2.95$, $sd = 1.06$) and Environmental safety ($M = 2.55$, $sd = 1.01$).

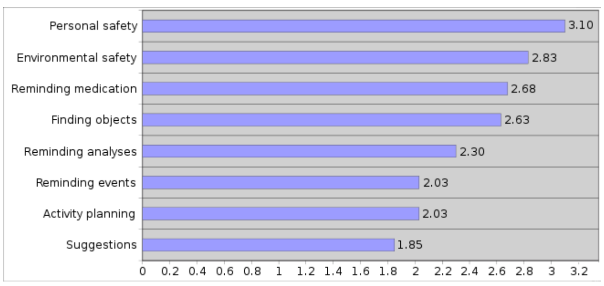

Figure 5: Utility of the domestic robot for everyday situations.

Resemblance to human beings.

With respect to the physical characteristics, the robot appears to be slightly pleasant ($M = 2.18$, $sd = 1.38$); as to this issue, however, our manipulation emerged to be effective, being the No-face version significantly preferred on the whole ($F_{(1,38)} = 6.34$, $p < .05$), specifically appearing both less mechanical ($F_{(1,38)} = 5.11$, $p < .05$) and less cold ($F_{(1,38)} = 7.25$, $p < .05$). The No-face version was also evaluated as having a significantly higher level of integration with the domestic environment ($F_{(1,38)} = 5.65$, $p < .05$) and a larger variety of advantages than the Face version, referring to ease of use ($F_{(1,38)} = 9.36$, $p < .01$) and a low need for repair ($F(1, 38) = 4.33$, $p < .05$) above all. No significant differences between the two versions, with reference to communication modalities ($F(1, 38) = 1.65$, n.s.) and perceived intrusion/ disturbance ($F_{(1,38)} = 1.55$, n.s.) emerged.

Finally, the emotional reaction (see Section 3 of the questionnaire) of elderly people to the robot was very good, scoring high the positive adjectives useful ($M = 2.90$, $sd = 1.10$), interesting ($M = 2.51$, $sd = 1.30$), and relaxing ($M = 2.38$, $sd = 1.14$), and being very low the negative adjectives scary ($M = .77$, $sd = 1.01$), overwhelming ($M = .97$, $sd = 1.40$), gloomy ($M = 1.00$, $sd = 1.36$), dangerous ($M = 1.05$, $sd = 1.23$), out of control ($M = 1.10$, $sd = 1.14$). The only significant difference between the two experimental conditions was referring to the adjective amusing ($F_{(1,37)} = 5.93$, $p < .05$), whose score was higher in the No-face condition.

In addition, elderly people seemed to be more likely to develop a psychological attachment towards the No-face version than towards the Face version ($\chi^2 = 6.11$, $df = 2$, $p < .05$).

Additional evaluation.

We have also analyzed the influence of other variables with respect to user preferences.

In order to measure the influence of age, familiarity with technologies and perceived health conditions on the evaluation of the robot, the above variables were analyzed by splitting respondents in two subgroups. A better evaluation of the robot's integration in the domestic environment by the younger elderly (up to 69 years old) than the older elderly (70 years old and more) emerged. This difference shows a tendency to significance ($F_{(1,38)} = 3.66$, $p < .08$). As to interaction modalities, the older elderly feel significantly more uncomfortable when interacting with a non-human agent ($F_{(1,38)} = 7.88$, $p < .01$). With respect to disadvantages associated to the presence of the robot, they were more afraid to have difficulties in using the robot ($F_{(1,38)} = 4.26$, $p < .05$) and in managing robot maintenance ($F_{(1,38)} = 4.33$, $p < .05$). The familiarity with technology did not show any significant influence on the robot's evaluation. Finally, elderly people with better perceived health conditions showed a fondness for teaching the robot how to perform tasks ($F_{(1,38)} = 7.89$, $p < .01$), a higher perception of integration with the home environment ($F_{(1,38)} = 6.07$, $p < .05$), and a greater ease of use ($F_{(1,38)} = 5.66$, $p < .05$) of the robotic agent. Elderly people who evaluated their health conditions less well, expressed a stronger preference for a robot being inert when not engaged in a domestic task ($F_{(1,38)} = 4.12$, $p < .05$), not autonomous in both taking decisions ($F_{(1,38)} = 4.64$, $p < .05$) and in giving suggestions ($F_{(1,38)} = 4.68$, $p < .05$).

4 Discussion

The study yielded a variety of interesting results, which can help shed light on possible future developments in research on the interaction between elderly people and domestic robots. Also, this study addresses some general acceptability requirements for robotic agents.

The evaluation of eight specific scenarios helps to single out the main concerns in the domestic experience of elderly people. Everyday life is scheduled across a variety of activities, but only some of them are considered of great importance. The management of personal and environmental safety was perceived as a very likely situation at home, which can become a problem when age increases. At the same time, the cognitive impairment associated with ageing can frequently entail difficulties in remembering to do things as well as what has been already done. These cognitive weaknesses are crucial especially when related to healthcare. For these activities, elderly people express a positive attitude towards the support of a robotic agent, which is perceived as a useful and appropriate device to overcome difficulties. With respect to other activities, which are not considered to be essential in everyday life, elderly people show a tendency to underestimate the likelihood of occurrence. The results in this case also show a diminished perception of the robot's potential utility. The general framework outlined in this study is in line with the model of successful aging put forward by [3], which stresses the role of selection and optimization of activities with increasing age, and the importance of compensation strategies to manage the loss of personal resources.

The overall evaluation of the robot highlighted a positive reaction towards a variety of specific characteristics. First of all, the robot is appreciated for its ability to communicate. Verbal interaction is highly valued and the interaction modalities involving a face-to-face relationship seemed to reduce a feeling of emotional distance from this device. Second, elderly people showed no manifest apprehension with respect to the integration of the robot in their home, appreciating the safeness of its ability to move and to avoid objects and obstacles. Nonetheless, the issue of safety emerged to be, again, a central concern in their experience, and they would like the robot to move in the domestic environment only when a specific task has to be performed. Third, the idea of the robot as a possible source of intrusion/disturbance in personal life, as depicted in previous research (see [32]) was not outlined: this underlines the difference between studies on mere representations, which may be biased in some way by the availability of examples of unrealistic robots, and research focusing on actual interactions, thus confirming the validity of our approach.

The practical benefits associated with with the assistive robot were clearly recognized. The robot can help people in the management of everyday activities requiring an efficient cognitive functioning, which is likely to be defective with increasing age. Above all, our results show a general enhancement in the psychological tranquillity in facing everyday situations, in that the robot can make elderly people feel safer, especially when they live alone. However, elderly people also showed to be aware of possible difficulties with the robot, which are mainly associated with its cost: a key concern for the price they have to pay, both to acquire the assistive robot and to maintain it clearly emerged.

The global picture outlined by these results is undoubtedly positive, and it is further corroborated by the analysis of the emotional characterization of the robot. The robotic agent was positively depicted in terms of utility, relaxation and interest, and hardly recognized as a source of danger, fear and other negative affects. A key role in promoting the acceptability of robotic agents is played by their impact on the behavior of the final user, his/her habits and routines, and on the dynamics of interaction with the home environment. This is because continuity in place experience is an essential factor in preserving personal identity [5]. With respect to this issue, the physical aspect of the robot emerged to be an important feature which can help support acceptability. Any allusion to human beings seemed to have an impact on the relationships between elderly people and their domestic environment. In particular, the No-face version of the robot was definitely preferred, and interestingly, the physical aspect proved to affect also the evaluation of other features which are apparently unrelated. In fact, the No-face version was not only perceived as less artificial and psychologically distant from the user, but also better integrated in the home setting and easier to manage. In other words, the better the aspect, the stronger the perception of positive qualities attributed to the robot.

Differential judgements were outlined with respect to socio-demographic and psychological characteristics of users, thus confirming previous studies [15]. Age emerged as an important factor in shaping the tendency for elderly people to feel comfortable with a domestic robot. The older elderly perceive greater difficulties in the interaction with and management of the robot. In addition, they show a higher concern towards possible problems in the integration of this device in the home environment. On the whole, they seem to be afraid, at least to some extent, of extreme modifications in their everyday environment [15], which in turn may lead to difficulties of adaptation [39]. Interestingly, familiarity with technologies did not show to affect the robot's evaluation, suggesting that acceptability for the elderly is not just a matter of frequency of use, but is presumably related to the perception of control on the environment when resources tend to decline. An interesting picture in this light was given by the analysis of the influence of perceived health conditions on the robot's evaluation. Elderly people in bad health conditions seemed to be mainly concerned with the potential difficulties and risks associated with the presence of the robot in the home, instead of considering the possible support in performing a variety of activities. In other words, the robot might be a further worry adding to their personal health concerns. Conversely, elderly people in good health conditions were more confident in the possibility of controlling negative aspects of this device, and were more aware of the benefits it can provide. For those people, the perception of good health turned into a stronger perception of everyday competence [37, 20] and self-efficacy [21, 4].

Overall, our study has shown how the availability of a situated prototype can greatly enhance the resolution of psychological evaluation. Our findings can be considered an intriguing starting point to address the issue of acceptability of robotic agents in the everyday life of elderly people.

5 Conclusions

In this paper we have presented the RoboCare Domestic Environment, an intelligent domotic environment equipped with an assistive robotic companion aimed at providing cognitive support for elder users who wish to maintain their independence. The smart home is the result of the integration of state-of-the-art robotic and software agent technology. After presenting the main components of the system, the article focuses on an experimentation aimed at validating the current capabilities of the environment with respect to the expectations of elder users.

A key feature of the assistive environment is an autonomous robot which acts as the primary interface between the cognitive support services provided by the multi-agent system and the assisted elder. Through the robot, the domotic services provide active surveillance of the elderly user at home. Specifically, the robotic mediator is capable of (a) contextually supporting the user (through verbal interaction) in every-day activities, as well as (b) identifying serious emergency situations and issuing appropriate alarms.

Two important features of the assistive robot have emerged as very relevant from the user analysis we have presented in this paper: (a) the ability to move robustly in the home environment, e.g., moving smoothly and safely, avoiding obstacles, etc., and (b) the ability to interact naturally with the elderly user. Indeed, these features had already been singled out as important in a preliminary analysis conducted before active development had commenced, and have guided our research throughout the project, particularly with respect to the mobility requirements. These studies will also influence our agenda for future work, particularly concerning aspects related to natural language interaction.

Other remarks have emerged from the analysis of tasks that the assistive environment as a whole is able to support. Tasks relative to safety, personal health, and object tracking have been evaluated as critical, and user response to our technological solutions in these areas is extremely positive. This suggests that it is important to foster advancements of assistive technology in these areas. According to our experience, this will require further investment in sensory technology, with a particular emphasis on integrating different types of environmental sensors.

Another interesting point which emerges from the evaluation is the relatively low appreciation of "suggestions". This is an important indication because it poses the question of whether this is due to poor communication capabilities on behalf of the robot, or to an effective lack of interest in these situations. Further analysis will be needed to inspect the possibility of improved added value with more sophisticated natural language interaction.

A final comment is orthogonal to the previous ones and concerns the need for multi-disciplinary competences for creating realistic proposals for socially assistive environments. As shown in this paper, the amalgamation of competencies in robotics, artificial intelligence and cognitive psychology has been a driving factor in the development of the RoboCare Domestic Environment. Given the particularly sensitive nature of assistive technology, future challenges in assistive robotics will most likely require an increasing degree of multi-disciplinary research to effectively address the many technical and psychological issues involved.

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