"Robotically Rich" Environments for Supporting Elderly People at Home: the RoboCare Experience

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Abstract

The aim of the ROBOCARE project is to develop an intelligent domestic environment which allows elderly people to lead an independent lifestyle in their own homes. This paper describes a testbed environment which simulates the home of an elderly person whose daily routines need to be monitored by human caregivers such as physicians or family members. We focus on the issue of how to enhance the robotic, sensory and supervising components of the system in order to achieve an environment which is at the same time pro-active and non-invasive.

1 Introduction

The long term goal of the research developed by the ROBOCARE project[1] is to contribute to raising the quality of life of elderly persons. In particular, we are pursuing the idea of developing support technology which can play a role in allowing vulnerable elderly people to lead an independent lifestyle in their own homes. This paper describes a testbed environment (Robocare Domestic Environment — RDE) aimed at re-creating the home environment of an elderly person whose daily routines need to be loosely monitored by human supervisors such as physicians or family members. The assisted person's home is equipped with some fixed and mobile environmental sensors, consisting in embedded domotic components as well as mobile robots endowed with rich interactive capabilties. All components of the system interact by means of a service-oriented infrastructure [Bahadori et al., 2004], and are coordinated by a supervision framework.

The goal of the proposed supervision infrastrucure is to preserve the independent lifestyle of a cognitively and/or physically impaired elderly person while committing to the least possible level of invasiveness. The environment must therefore adapt to the assisted person's needs: the level of pervasiveness of the supervision framework in the assisted person's daily routine must be directly proportional to the level of handicap. The aim of this paper is to describe the components, algorithms and methodologies we have developed in order to achieve such a highly customizable supervision framework.

Our main objective is to develop an intelligent environment which is at the same time "active" (in the sense that it can effectively monitor the assisted person) and also not invasive. With the term non-invasiveness, we express that the actions performed by the system as a whole on the environment should occur pro-actively and only when they are beneficial to the assisted person[2]. Given the diverse nature of the technology involved in the RDE, implementing a non-invasive system implies a rich array of design issues, which we begin to address in this paper. After giving a brief system description in the following section, we proceed in a bottom-up fashion: section 3 describes the key features of the robotic components, addressing first the aspects related to their mobility, and then the user-interaction schemes that have been adopted; section 4 describes the mechanism by which the caregivers model the behavioural constraints which are mapped against the sensor-derived information by the supervision system; we conclude with a discussion on possible future developments.

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[1]http://robocare.istc.cnr.it.

[2]Recent pshychological studies [Giuliani et al., 2005] address issues related to the acceptability of technology by elderly people.

2 System Description

The overall system architecture is described in figure 1. The central component is the supervision framework, whose goal is to survey the daily routines of the assisted person and to coordinate the behavior of the embedded technological components (sensors and robots) accordingly. As shown in the figure, it consists in two fundamental modules: a Constraint Manager (CM) and an Event Manager (EM). The CM maintains a set of tasks and complex time constraints which represent the assisted person's nominal daily routine, and are cast as a scheduling problem. The tasks and constraints which compose the nominal schedule are defined by the caregivers (doctor and family member in the figure). Moreover, the CM matches the prescriptions represented by the nominal schedule to the actual behaviours of the assisted person as they are perceived by the sensors. The execution monitoring technology [Cesta and Rasconi, 2003] built into the CM propagates the sensor-derived information and detects any deviations in the assisted person's behavior from the nominal schedule. The key feature of the CM is its capability of recognizing the degree to which the assisted person's real behaviour adheres to the caregivers' prescriptions.
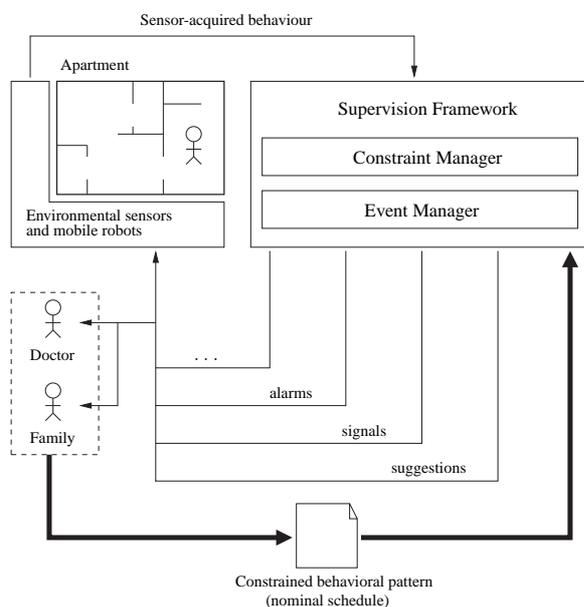

Figure 1: Overall system architecture of the ROBOCARE Domestic Environment.

The diagnosis performed by the CM during propagation is processed by the EM. It is the responsibility of the EM to trigger the appropriate event according to the specific behavioral constraint which is violated. For instance, the system should set off an alarm if,

based on sensor-derived information, the CM detects that the assisted person's current behaviour compromises the successful completion of another important task. The EM defines how the system reacts to the contingencies in the nominal schedule by triggering events such as robot service invocations, alarms, suggestions, or simple logging of events.

The robotic subsystem which enhances the assisted person's domestic environment is composed of fixed and mobile components. Also these components have been engineered to reflect our main objective of low invasiveness. To this end, we have equipped our robots with localization and path-planning strategies which are oriented towards maintaining high levels of safety while ensuring adequate mobility. Moreover, human-robot interfaces have been developed using simple graphical schemes of interaction based on strong ergonomy and usability requirements. Solutions such as the use of clearly distinguishable buttons, high-contrast color schemes and input/output redundancy have been employed in an attempt to minimize the impact of high technology on the end-user.

3 Ergonomic Embedded Technology

The introduction of robots in domestic environments is a complex issue both from the technological point of view (houses are highly de-structured) and from the typology of the end-user (elderly people do not like to change their habits or to have their spaces reduced). An elderly person may have reduced physical and/or cognitive capabilities which can represent a barrier for the use of high-tech instrumentation.

Psychological studies [Scopelliti et al., 2004] show that in order to be successful in this project it is necessary that the elderly people perceive the robots as "friendly creatures" which are of some help in their every day life. The cohabitation with another beings, even though artificial, has beneficial effects on the individual, in the same way as with pets.

Hence the need to endow the robots with the capability to interact with people according to natural communication schemes: oral dialogues, facial expressions, prossemic and kinesic signals.

3.1 Robotic and sensory system

At the present stage of development, the RDE hosts three types of embedded technological components:

- stereo color camera based sensor, located in fixed positions of the environment;

- Pioneer 3 AT mobile robots, equipped with a ring of sonars, a Sick laser range finder device and a color omni-directional camera;

- palm devices for user interaction.

These three components are able to share information through a wireless network which covers the whole environment, and interact according to a service-oriented paradigm [Bahadori et al., 2004]. Our work focuses on monitoring-specific services, namely *People tracking* and *People localization* services provided by the fixed stereo camera, a *Objects Delivery* service provided by the mobile base, and a *Visualize* service provided by a Personal Digital Assistance, which allows a human operator to visualize the current state of the mobile robot through the palm device.
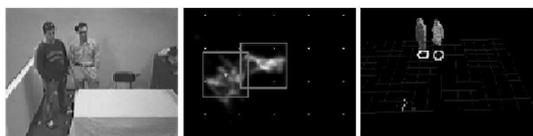

Figure 2: The different phases for people localization: original image, planar view, and 3D view. The two subjects are correctly mapped also in the presence of occlusions.
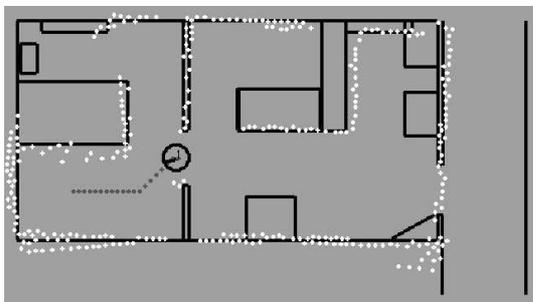

Figure 3: The robot autonomously navigating the Robo-Care environment.

The *People localization* service is invoked to recognize a human being who is present in the environment, and to compute his/her coordinates with respect to the camera (see figure 2). The *People tracking* service is able to track a person in the environment following its movements. Moreover, the stereo camera is capable of correctly mapping partially occluded elements of the scene. The *Object Delivery* service allows the mobile base to safely navigate the environment bringing a light-weight object in a desired position. In particular, the robot is able to localize itself inside the environment, compute the best path to reach the desired position and follow the path while
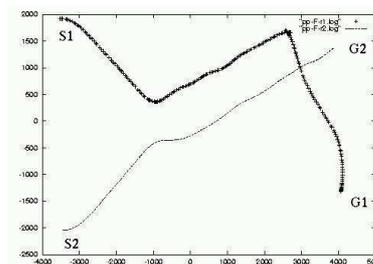
(a)
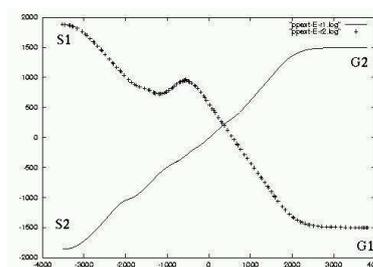
(b)

Figure 4: Behavior of the robot without considering the obstacle dynamics (a), and behavior of the robot when the obstacle dynamics are taken into account (b).

avoiding possible unexpected obstacles such as moving person (see figure 3). The *Visualize* service exports the internal state of the robot to a palm device, in particular the service provides the robot's position in the environment, the current action the robot is performing (e.g., following a path), the current sensor readings (e.g., the obstacle detected through the sonars), or an image of the environment obtained with the on board camera (see next section for a detailed description).

A main requisite for the design of the embedded technology is to provide flexible solutions which can be easily integrated inside the environment. A necessary condition for minimizing the level of invasiveness of the technology is that it should not require re-engineering the environment. Flexibility and adaptation to the environment are crucial issues for the embedded technology, because the deployed devices are often intended to interact physically with the target user, and thus can interfere with everyday activities.

In order to satisfy these specifications, we have adopted a series of design choices aimed at adapting robots and hardware devices to the environment where they should operate. A first, fundamental issue is robot mobility. The navigation capabilities of

robots are achieved without any changes to the domestic environment; no artificial markers are needed to localize a robot, and its path planning capabilities are designed to achieve safe navigation in cluttered environments with object of any shapes. In this way, the target user is not required to adapt the furniture or the colors of his or her living environment. Moreover, the path planning method (as described in [Farinelli and Iocchi, 2003]) explicitly takes into account the possibility of having persons moving in the environment. The method is able to take into account the movements of other persons in the environment, yielding in order to allow them to pass first. The people localization service does not rely on any device or particular cloth the target users should ware, rather, it automatically detects a person based on a fore-ground extraction method [Bahadori et al., 2004].

Figure 5: The Palm PDA interface after issuing the *WhatRUDoing* command.

The control of the robot is based on a high level representation of the world and on cognitive capabilities. For example, the robot is able to represent and recognize objects in the surrounding environment and to localize itself inside the environment. Since all the components are connected via the wireless network, in the execution of such behaviors the robot can use the information acquired by the stereo camera to map a person inside its own representation of the world. Using such high level information, the robot is able

to execute complex plans which comprise the execution of several atomic actions. In this way the robot can perform a set of high level behaviors making it much easier for humans to interact with it.

All the components previously described have been tested and evaluated both in specific experiments and in coordinated demos. The interested reader can find more details on the specific methods in [Farinelli and Iocchi, 2003] and [Bahadori et al., 2004]. In particular for the path-planning method, specific experiments show how the behavior of the robot has improved, considering in the path-planning process the dynamics of the obstacles. Figure 4(a) and figure 4(b) represent the paths followed by the robot when a moving obstacle crosses its way. The robot's initial position is S_1 and its final destination is G_1. In figure 4(a) the path planning method does not take into account the obstacle dynamics (i.e., the velocity vector of the obstacle), while in figure 4(b) such information is conveniently exploited and the robot decides to pass behind the obstacle generating a path which is not only more convenient, but also safer.

3.2 Human Robot Interfaces

The main interaction between the assisted person and the system occurs through the use of a PDA (Personal Digital Assistant). The key idea is based on the fact that the PDA constitutes a sort of remote control as it represents the means by which the user can ask for service activation. The PDA is an instrument characterized by an extremely light weight and this makes it suitable to be easily carried by the assisted person; as a downside, its small size reduces the possibility of using its touch-screen as a full-functionality interface. For this reason it is necessary to implement some input/output features on the PDA's audio channel. The communication between the PDA and the rest of the system occurs in wireless mode.

The exported services are organized in two main categories depending on which event triggers them: i) the occurrence of a specific event, and ii) a user request. Services belonging to the first set are triggered either in presence of some kind of errors (for instance, *unrecognized vocal command*) or on occurrence of scheduled activities (e.g., *it's time to take the medicine* or *the news will start in five minutes*).

The services triggered by a user's request are tasks which are obviously not present in the original schedule.

Let us give an example of interaction with a single robotic agent. The services provided by the agent can be summarized as follows:

ComeHere instructs the robot to reach the user (which is equivalent to reaching the PDA)

WhatRUDoing allows to visualize the activity performed by the robot through the use of the onboard camera and receive some oral information related to the same activity

Go(*where*) instructs the robot to go to the place specified by the user in the parameter *where*

Stop instructs the robot to interrupt all the activities requested by the user (the activities belonging to the original schedule obviously continue their execution)

The interface main screen provides four buttons one for each of the previous services. Such functionalities are also associated to the four programmable buttons of the PDA. In case the user pushes the *Go* button, the *where* parameter can be specified by selecting the destination room directly from the environment map that appears on the screen. When the user selects the *WhatRUDoing* command, the PDA will reproduce both the instant image coming from the on-board camera, as well as the position of the robot in the house (see figure 5); clicking on the previous image returns a full screen picture, for better visualization. Another click leads back to the initial menu.

4 Monitoring Daily Routines

Now that we have described some aspects related to the acceptability of the sensors and robotic components embedded in the RDE, we address some issues related to the form of interaction between the supervision framework and the caregivers. In this section we describe the nature of the behavioral constraint specifications which are defined by the caregivers for the supervision framework to monitor. In particular, we show a modeling framework which allows the caregivers to harness the full expressiveness of the underlying category of scheduling problems.

As mentioned, the assisted person's daily behaviour is modeled as a set of activities and complex temporal constraints. The core technology we deploy consists in a CSP-based scheduler [Cesta et al., 2001] equipped with execution monitoring capabilities [Cesta and Rasconi, 2003], which is able to deal with rather complex scheduling problemsThis high complexity is supported by a highly expressive scheduling formalism which allows, among other things, for the definition of complex temporal relationships among tasks, such as minimum and max-

Operator	Semantics
create_task(t,min,max)	Creates a task named t whose minimum and maximum durations are min and max.
create_res(r,cap)	Creates a resource named r whose capacity is cap.
set_res_usage(t,r,use)	Imposes that task t uses use units of resource r.
create_pc(t1,p1,t2,p2,x)	Imposes a precedence constraint of x time-units between time-point p1 of task t1 and time-point p2 of task t2.

Figure 6: The four elementary operators for building scheduling problem instances.

imum time lags[3]. The need for a highly expressive scheduling formalism[4] for the purpose of specifying the assisted person's behavioral constraints can be appreciated in the fact that often the constraints consist of complex time relationships between the daily tasks of the assisted person. Also, given the high degree of uncertainty in the exact timing of task execution (a person never has lunch at the same time every day, etc.), it is necessary to model flexible constraints among the tasks, while admitting the possibility of hard deadlines or fixed time-points. Overall, the aim is not to control task execution, nor to impose rigid routines, rather it is to monitor the extent to which the assisted person adheres to a predefined routine, defined together with a physician or family member.

The technical details of how the caregivers' prescriptions are cast into a scheduling problem is outside the scope of this paper. It is sufficient to mention that the expressiveness of the temporal problem which is cast is completely captured by the four basic operators shown in figure 6.

What we would like to emphasize here is that such a versatile specification formalism allows us to model with very high precision the behavioural constraints for the assisted person. This ability to describe real-

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[3]As well known in the scheduling community, the introduction of maximum time lag constraints increases problem complexity from P to NP.

[4]Similar attempts at using core solving technology in domestic and health-care environments have been made (e.g. [McCarthy and Pollack, 2002; Pollack et al., 2002]).

ity with the required degree of granularity makes it possible to always maintain the desired level of flexibility in the specification of the necessary constraints. Indeed, this implies a low level of invasiveness because the synthesized behavioral pattern is never constrained beyond the real requirements prescribed by the caregivers.

Clearly, this versatility comes at the cost of a high complexity of the specification formalism. Indeed, the four operators shown above are rather straightforward, but building a complex scheduling problem using these operators can be a demanding task even for a scheduling expert. Moreover, modeling behavioral constraints in the context of the RDE in this fashion would turn out to be not only tedious but also definitely out of reach for someone not proficient in scheduling.

A key issue is thus represented by the fact that the monitoring framework should be designed to meet the requirements of different types of end-users, each having different needs: for instance, a doctor might be interested in monitoring activities which pertain to health control, while the assisted person's relatives might instead be concerned with the recreational aspects of the person's daily life. In order to enable these different users to easily interact with the supervision framework we have deployed in the RDE, we employ a knowledge representation layer for problem modeling, built around the core scheduling technology which implements the CM module. This layer allows the end-user to easily specify behavioural constraints for the assisted person while ignoring the technicalities of how these constraints are cast into the underlying core scheduling formalism[5]. In the following section we describe by means of a simplified example how the introduction the knowledge representation layer makes our monitoring technology accessible to the caregivers.

4.1 Modeling Framework

In order to provide the caregivers with a modeling tool which hides the technology-specific details while maintaining the necessary expressiveness, we proceed in two steps:

Domain definition. The first step is to define the types of tasks which are to be monitored and the types of constraints which can bind them. This equates to formalizing the types of medical requirements and behavioral patterns which can be prescribed by the human supervisors. The result of this requirement

analysis is what we call a *domain description*. A domain encapsulates the scheduling-specific knowledge for the definition of the behavioral constraints, and provides usable "building blocks" for the particular category of caregiver to use. These building blocks, called *constructs*, constitute a terminology which is tailored to the expertise of the particular caregiver.

Instantiation. The caregivers can at this point employ the particular domain which has been built for them to define the constraints for the assisted person. A physician, for instance, may use the "RDE-medical-requirement" specification terminology specified in the domain which was created for such purposes. A domain definition process which is correctly carried out yields a collection of constructs which match the supervisors' usual terminology, and mask completely the scheduling-specific knowledge otherwise needed for schedule specification. The particular requirements for the assisted person are thus defined in the form of construct instantiations, which are consequently passed on to the monitoring system.

Once the nominal schedule is established by the caregivers, all execution-time variations to the schedule are taken into account by the execution monitor: by polling the sensors, the execution monitor gathers information on the real state of execution of the tasks, and employs the CM to propagate any variations. The key idea is that if any of these variations violate a constraint then the proper actions are triggered by the EM (such as alarms, reminders, and so on).

4.2 RDE Domain Formalization

We now show a simplified example domain specification which defines some typical behavioral and medical requirements of the assisted person. As mentioned above, this domain defines a set of constructs any instantiation of which is an "encoding" of a set of requirements to which the assisted person's routine should adhere. In the following paragraph, we omit the details of the construct definitions, limiting the presentation to a simplified description of how the constructs define the underlying scheduling problem.

Domain definition. Let us start with the basic construct for defining the assisted person which is being supervised:

```
(:construct assisted_person
  :parameters (name) ...  )
```

---

[5]The scheduling specific details as how this compilation occurs are outside the scope of this paper, and are described in [Cesta et al., 2005].

This construct defines a binary resource corresponding to the assisted person. This reflects the assumption that the assisted person carries out at most one task (of the tasks which are monitored) at any instant in time. This is guaranteed by the fact that every construct in this domain uses exactly one unit of this binary resource. It should be clear that behaviors in which there is some degree of concurrency can be modeled by increasing the capacity of this resource.

Another requirement of the monitoring system is to oversee the dietary habits of the assisted elderly person. To this end, we define the following three constructs:

```
(:construct breakfast
   :parameters (person start end) ...  )
(:construct lunch
   :parameters (person start end min_bfast
      max_bfast) ...  )
(:construct dinner ...   )
   :parameters (person start end min_lunch
      max_lunch) ...  )
```

The reason for modeling breakfast, lunch and dinner (rather than a single `meal` construct) is because the caregivers need to ascertain the regularity of the assisted person's diet. For instance, through the specification of the `min_lunch` and `max_lunch` parameters, it is possible to model the upper and lower bounds between one meal and another. Thus, the instantiation (`dinner 1200 1260 180 360`) in the problem definition (time units are in seconds) equates to stating that (1) the assisted person's nominal time for dinner is from 8 pm to 9 pm, (2) the assisted person should have dinner at least three hours after lunch, and (3) he or she should not have dinner more than six hours after lunch.

In addition to the dietary constraints, medical requirements are also specified by means of the `medication` construct:

```
(:construct medication
   :parameters (person product dur min_time
      max_time) ...  )
```

The construct prescribes that a medication cannot be taken before `min_time`, nor after `max_time`, which in turn are user definable parameters of the construct. This is achieved by constraining the start time-points of the task with the beginning of the time horizon. Similarly, a construct which imposes lower and/or upper bounds on medication with respect to meals is provided:

```
(:construct meal_bound_medication
```

```
   :parameters (person product dur meal
      min max) ...  )
```

For example, by specifying (`meal_bound_medication roger aspirin 5 lunch 0 25`), we model that Roger can take an Aspirin potentially immediately after lunch, but without exceeding twenty-five minutes.

Instantiation. A problem specification based on the domain described above is shown below:

```
(define (problem test_prob)
   (:domain RDE)
   (:specification
      (assisted_person jane)
      (breakfast jane 480 510)
      (lunch jane 780 840 240 360)
      (dinner jane 1170 1290 300 360)
      (meal_bound_medication jane aspirin 5
         dinner 0 20)
      (medication jane herbs 10 720 1200)
      (medication jane laxative 5 1020
         1260)))
```

It is interesting to point out some of the design decisions which were made in the domain definition. Notice that all tasks have a fixed duration, a fact which may seem counter-intuitive in this domain. For instance, we have no reason to believe that Jane's breakfast lasts half an hour, nor can we commit to any other projected duration since it will always be wrong. On the other hand, establishing a lower or upper bound on the duration of her meals would just as well be unfounded. Thus, this uncertainty is dealt with by the CM, which dynamically adapts the duration of the tasks to the sensors' observations. The durations of the tasks are thus kept fixed in the problem specification since the execution monitor does not trigger an alarm when they are not respected. An alarm may however be triggered in the event that the sensed deviation from the nominal duration causes other serious violations of behavioural constraints in the nominal schedule. In general, the constraints modeled in the domain can be treated variety of ways: some constraints, such as task durations in the specific example shown above, are "soft", meaning that their purpose is solely that of modeling the assisted person's nominal behaviour; other constraints, such as the relationship between meals and medication in the above example, are "hard", meaning that if they are violated, this represents a contingency which calls for a specific event (such as an alarm, a notification and so on). In the light of these considerations, the constructs defined in the domain must be seen as elements of a language with which a caregiver can express (1) which events in the daily routine he or she

would like to supervise (e.g., Jane should take an Aspirin every day), (2) how these events are related to each other in terms of "causality" (e.g., since Aspirin needs to be taken with a full stomach, having dinner is a precondition for taking an Aspirin), and (3) the degree to which the assisted person should comply to the nominal schedule (e.g., Jane cannot wait more than twenty minutes after she has finished dining to take her Aspirin).

5 Conclusion and Future Work

In this paper we have described some aspects related to the design of an intelligent domestic environment for the care of elderly people. We have mainly focused on the design choices which minimize the level of invasiveness of the embedded technology. We have shown how this goal is pursued both in the development of the hardware components and in the implementation of the supervision framework. As we have seen, endowing domestic robots with more "human-centered" features, such as intelligent obstacle avoidance schemes and intuitive human-robot interfaces, is critically important if robotic components are to be accepted in domestic environments. Similarly, we strive to provide caregivers with intelligent monitoring tools which are also extremely configurable around the very particular requirements of a particular assisted person. We argue that adaptability is a determining factor for the successful deployment of ambient intelligence in domestic environments.

The work we have presented in this article represents a first step towards a fully-customizable supervisory system, and is part of a larger effort started in 2003 with the ROBOCARE project, in which the issues related to human-robot interaction are extremely relevant. While the question of broadening the scope of application of robots for the care of the elderly is still a very open issue, we believe that one important reason which justifies a wider utilization in contexts such as the RDE lies in concealing their qualities as technological aides behind a friendly appearance.

Acknowledgements

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