

## Research Article

Gabriella Cortellessa, Riccardo De Benedictis, Francesca Fracasso, Andrea Orlandini, Alessandro Umbrico, and Amedeo Cesta\*

# AI and robotics to help older adults: Revisiting projects in search of lessons learned

<https://doi.org/10.1515/pjbr-2021-0025>

received November 30, 2020; accepted May 12, 2021

**Abstract:** This article is a retrospective overview of work performed in the domain of Active Assisted Living over a span of almost 18 years. The authors have been creating and refining artificial intelligence (AI) and robotics solutions to support older adults in maintaining their independence and improving their quality of life. The goal of this article is to identify strong features and general lessons learned from those experiences and conceive guidelines and new research directions for future deployment, also relying on an analysis of similar research efforts. The work considers key points that have contributed to increase the success of the innovative solutions grounding them on known technology acceptance models. The analysis is presented with a threefold perspective: A *Technological* vision illustrates the characteristics of the support systems to operate in a real environment with *continuity*, *robustness*, and *safety*; a *Socio-Health* perspective highlights the role of experts in the socio-assistance domain to provide contextualized and personalized help based on actual people's needs; finally, a *Human* dimension takes into account the personal aspects that influence the interaction with technology in the long term experience. The article promotes the crucial role of AI and robotics in ensuring intelligent and situated assistive behaviours. Finally, considering that the produced solutions are *socio-technical systems*, the article suggests a *transdisciplinary* approach in which different relevant disciplines merge together to have a complete, coordinated, and more informed vision of the problem.

**Keywords:** assistive technologies, intelligent artefacts, robotics, artificial intelligence

## 1 Introduction

Life expectancy is increasing today [1] and the number of people getting older and needing support is consequently also growing. Most seniors aim to age in place, that is to stay as long as possible in their own environment [2]. Nevertheless, changes due to advancing age pose challenges that are difficult to solve and overcome [3]. In this perspective, research is focusing attention on the creation of Information and Communication Technology (ICT)-based systems and more recently on robotic systems to help older adults both in physical activities (physical assistive robots) and in intellectual and cognitive activities (social assistive robots [SAR]), distinguishing between physical needs and intellectual/relational relationships of people at different stages of advanced life [4]. Robots in these cases are proposed as tools to compensate for dysfunctions and face age-related challenges [5]. Very often robotic systems are inserted in wider and more complex contexts that include different technologies to provide more complete and contextualized assistance services. Typically, this kind of technology reproduce the *sense-plan-act* model [6] that is ensured by a combination of: (a) environmental and physiological sensors, for monitoring the status of the environment and the senior; (b) artificial intelligence (AI) modules for providing intelligent services such as activity recognition, reminders, proactive suggestions, coaching, etc.; and (c) actuators, intelligent interfaces, and robotic platforms for delivering the assistive services to the seniors [7]. In line with this need, the theme of Active Assisted Living (AAL) has been introduced as a term for a field of technology research and development with the general aim to facilitate and extend independent living (ageing in place) of older adults exploiting the integrated work of smart sensors, actuators, AI technology, and also robots. In this article, we

\* **Corresponding author: Amedeo Cesta**, CNR, Italian National Research Council, Institute of Cognitive Science and Technology, Via San Martino della Battaglia 44 I-00185, Rome, Italy, e-mail: amedeo.cesta@istc.cnr.it

**Gabriella Cortellessa, Riccardo De Benedictis, Francesca Fracasso, Andrea Orlandini, Alessandro Umbrico:** CNR, Italian National Research Council, Institute of Cognitive Science and Technology, Via San Martino della Battaglia 44 I-00185, Rome, Italy

retrospectively describe our experience in developing systems that integrate AI and robotics to support frail older adults, enriching it also with the analysis of the state of the art on similar experiences and research projects. The contribution of this article is an analysis of these experiences to derive lessons learned and guidelines as well as to highlight those points that are still open, which might constitute interesting research challenges for the future.

The article is organized as follows: Section 2 describes authors' progressive path from the development of intelligent systems towards the deployment of such systems in ecological settings. For each step of the progression, some lessons learned are underscored as pieces of a large mosaic; Section 2.2 overviews similar research effort available in the literature; Section 2.3 analyses the experiences as a whole and derives some lessons learned highlighting weaknesses and good features of systems for user acceptance; Section 3 provides remarks for future directions of research, while Section 4 ends the article.

## 2 Towards the deployment of end-to-end systems

Figure 1 shows the temporal succession of some of the research projects that have led, over the years, to an ever tighter integration of robotics and AI. The figure, in particular, shows a subdivision into three phases: a first one in which the work was mainly carried out in *laboratory settings* under controlled conditions, with a project named

ROBOCARE which was one of the first experiences in Europe integrating AI with robotics with a multidisciplinary approach; a second phase during which, having a more robust and mature technology available, it was possible to move the testing of technology into *ecological domestic contexts* with the possibility of carrying out also long term experiments in domestic environments with two subsequent projects: EXCITE and GIRAFF-PLUS; the most recent third phase that revisited the research ideas previously touched upon, and also enabled an effort to test the technology in *heterogeneous contexts* (e.g. domestic environments, hospitals, residential care facilities, etc.). The current SI-ROBOTICS project pursues modularity, adaptability, and also robustness of the proposed solutions.

### 2.1 Research path and approach

Following the timeline of Figure 1 we here briefly describe the overall objectives of the mentioned research projects, highlighting their key ingredients and summarizing the evaluation results and the general lesson learned.

The approach to present our research experiences follows the chronological order of development, which is strictly influenced by the *technological readiness* of the sensors, the robotic platforms, and AI components and their ability to be used in the long term in real contexts. The basic idea in all projects is to create an integrated system to monitor the activities and health of an old person and to provide support services in daily life. From this perspective, the services range from *activity recognition* and *environment monitoring*, to *reminders*, to

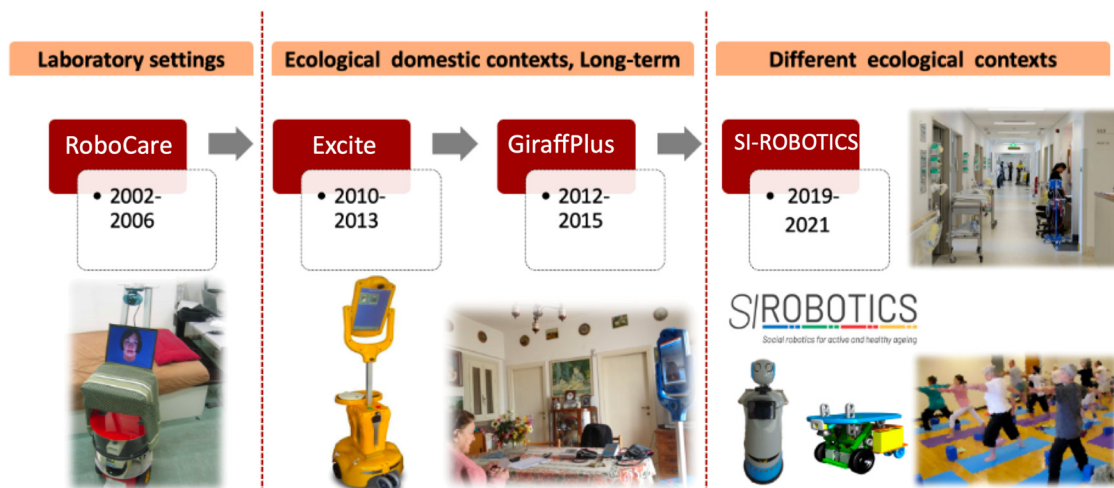


Figure 1: A summary timeline showing the integration of AI and robotics in our research projects.

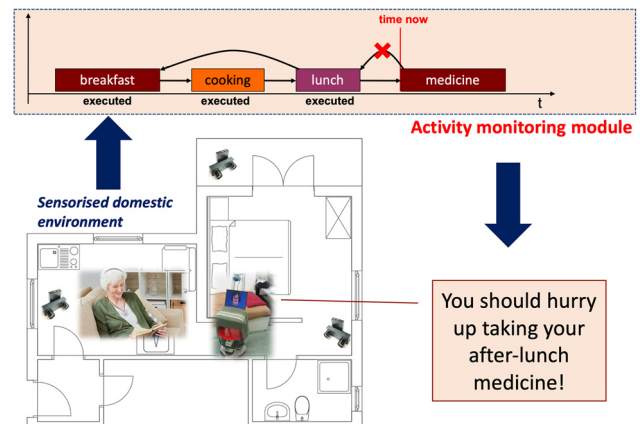
*proactive interaction* for suggesting healthy lifestyles, and to *autonomous robot behaviour*. The presentation is therefore influenced by the robustness of the technology as an enabling factor for the installation in real environments and for the testing of systems with fragile users. Starting from ROBOCARE, the first technological challenge was linked to the robotic platform, which was not yet ready and robust to operate in the long term and continuously. The challenge that emerged was therefore to create a robust robot capable of operating continuously in a real environment, also paying attention to aesthetic aspects to favour its acceptance by users. This challenge was addressed in the EXCITE and GIRAFFPLUS projects using a commercial telepresence robot and more advanced monitoring sensors. The open challenges in this case concerned the provision of advanced services, the need to customize the behaviour of the robot, and to adapt the technology to the context of use. The latest project, SI-ROBOTICS, tries to tackle this challenge, proposing a modular solution that can be applied to different assistance contexts by adapting its behaviour accordingly.

Looking at the evolution of these projects it can be noted that the development and integration of robotics and AI have enhanced both the complexity and the ambition of services that can be realized to support older adults. The availability of increasingly complex systems and services raises new challenges that see this kind of (autonomous) system moving from pure technical solutions to socio-technical systems where humans (e.g. older adults and caregivers) play a central role and are themselves part of the systems. This kind of systems represents holistic solutions that integrate the technological components into organizational processes [8].

### 2.1.1 The ROBOCARE experience

The ROBOCARE project [9] has been one of the first research efforts in Europe specifically focused on the integration of AI and robotics technology for domestic assistance services. The result of our research is a prototypical intelligent home (the ROBOCARE domestic environment [RDE]), in which sensors, robots, and other intelligent agents coordinate to provide support in the daily activities of an older adult [10].

**The ROBOCARE technological ingredients.** Since the beginning, the key idea pursued in the project was to create an instance of an End-to-End system for assisting older adults. As shown in Figure 2, the ROBOCARE prototypical smart home comprises a single mobile robot and an intel-



**Figure 2:** The ROBOCARE Domestic Environment: AI-based technology reasons on monitored activities and issues warnings and alarms through a robotic platform.

ligent stereo-camera. The robotic platform was a Pioneer2 equipped with Robot Development Toolkit functional middleware [11] that integrates the capabilities of a simple path planner and a state of the art Simultaneous Localization And Mapping algorithm [12] driven by SICK Laser Scanner data. A separate subcomponent for robot interaction skills was coupled with the robotic platform. The interaction skills were composed of (a) a “talking head” called Lucia, an off-the-shelf software developed at ISTC,<sup>1</sup> which was also endowed with speech synthesis functionalities based on the elaboration of specific “content files” in the text format; (b) a speech recognition system called Sonic, a tool developed at the University of Colorado [13]; and (c) a simple InteractionManager developed within the ROBOCARE project consisting of a rule-based system that fires situation-action rules by activating the specific submodules that are under the manager’s responsibility.

These components are integrated with an AI-based Activity Monitor, the aim of which is to react to unexpected behaviours of the assisted person [10]. The general idea of the Activity Monitor is to “observe” the assisted person’s actions and maintain an updated representation of the person’s and the environment’s state. Based on these observations, the system employs its automated reasoning capabilities of assessing whether the person’s activities fall within predefined *behavioural patterns* defined by caregivers on the basis of the user’s medical needs that can be considered as desirable for the assisted persons. These patterns are represented in the form of

<sup>1</sup> P. Cosi, Lucia, ISTC-CNR, Padova, <https://www3.pd.istc.cnr.it/piero/LUCIA/> [last accessed on August 1, 2021].

flexible schedules, predefined by a caregiver as an initialization phase of the system, which are reasoned upon by means of state of the art scheduling technology. The system's inference capabilities allow us to project the person's activities in time and to synthesize plans to compensate anomalies in the assisted person's behaviour. Examples of such plans are the speech acts through which the system warns a person of inconsistencies, which can emerge as a consequence of his/her current actions (e.g. suggestions to take the "after lunch medicine"). The main focus of the overall smart environment is to ensure, through daily activity monitoring, the adherence of the assisted person's routines to healthy behavioural patterns issuing suggestions or warning.

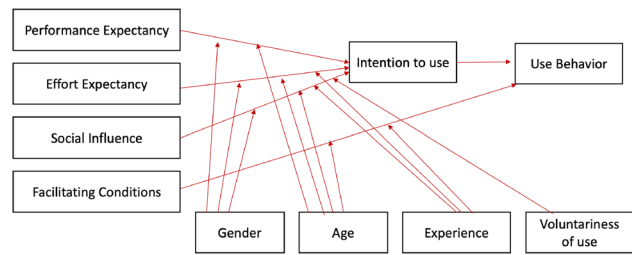
**Evaluation in laboratory settings.** One of the interesting aspects of this project concerned the video-based evaluation made with potential users of the system. In particular, eight videos were produced that described representative scenarios of possible interaction between older adults and the robot:

1. Environmental safety;
2. Personal safety;
3. Support in finding objects;
4. Support in the management of daily activities;
5. Reminders for medicines;
6. Reminder for medical appointments;
7. Reminders of events;
8. Healthy lifestyle tips.

After watching the videos, the participants replied to a questionnaire that investigated aspects such as *plausibility* of the proposed scenarios and *usefulness* of the services offered by the robotic platform and *acceptance*.

This article rereads the results of the evaluation in the light of the acceptance models of technology providing an overall and original view of the works described in refs [14,15]. In particular, we consider the UTAUT model [16].

The theory (Figure 3) states that there are four key constructs: (1) *performance expectancy*, (2) *effort expectancy*, (3) *social influence*, and (4) *facilitating conditions*. The first three are direct determinants of *usage intention and behaviour*, and the fourth is a direct determinant of *use behaviour*. *Gender*, *age*, *experience*, and *voluntariness of use* are posited to moderate the impact of the four key constructs on *usage intention and behaviour*. Under the lens of this framework, a high perception of usefulness towards the robot emerged from the evaluation. It was especially true for those tasks ensuring personal (detection of medical emergency and warning to a caregiver) and environmental (warning of potential dangerous situations)



**Figure 3:** The UTAUT – unified theory of acceptance and use of technology.

safety, and for tasks aimed at providing cognitive help while supporting in the daily activities. In line with these findings, the persons expressed more intention to use and higher acceptance in case of preserving both environmental and personal safety. Furthermore, a clear distinction between important and unimportant activities to be performed at home emerged. In the activities which are perceived of greatest relevance (personal and environmental safety), the autonomy of the robot in the management of the home environment and in taking decisions proved to be a very useful resource. In the situation involving an emergency, indeed, the preference for the robotic support is higher so as the perception of utility scores. Conversely, with respect to activities which are not considered to be essential in everyday life, elderly people show a tendency to assign a low score on likelihood of occurrence and even lower scores on usefulness and preference. The system has been judged as easy to use and the emotional impact on the respondents was essentially positive describing the system as relaxing, interesting, and absolutely not uncontrollable, gloomy, or dangerous. It emerged also a relation between perceived usefulness and acceptance and personal aspects. More specifically, it seems that people with a better perceived health conditions are more inclined to accept the system and judge it as more useful. Some concerns have also been expressed. Among them there were the worry about financial costs, the risk of not being able to manage technology due to a possible lack of knowledge. Finally, older adults manifested a sort of apprehension towards autonomous decision making and the risk to lose control and becoming dependent of the system and its services.

**Lessons learned.** The ROBOCARE experience was very useful for deriving lessons learned both from a technological and human factors point of view. The integration of different technology to provide intelligent services was an innovative and well accepted idea. Nevertheless, this experience also highlighted some weaknesses.



**Shortcomings:** The technology was preliminary and not mature enough for a real deployment. For this reason, it was impossible to carry out experimentation neither by deploying the system in real houses nor by setting up laboratory experiments. This, of course, prevented users from experiencing the technology in their daily routine and consequently the study results from providing additional important information like the impact on the daily living and the acceptance in the long term. Therefore, a key related challenge can be summarized as follows:

The *continuity of use* is a key challenge in robotics especially if the technology is intended to help fragile people.

In this respect, a robotic platform should be robust enough to guarantee a continuous use in real-world conditions and should also support users in relevant and important situations. Additionally, the evaluation highlighted also the relevance of Intelligent Environments that cooperate to have a more informed and contextualized knowledge of both users' and environmental status. The involvement of potential users as key driving factors is also paramount together with a multi-disciplinary approach.

In fact, one of the most original contributions of ROBOCARE was the multidisciplinary approach:

Multidisciplinarity is crucial to build solutions that are technologically solid but also well accepted by users.

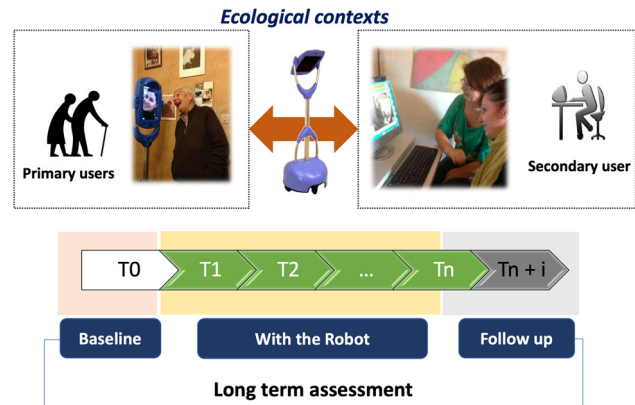
The results related to the distinction between important and unimportant activities suggest, on one hand, to have a proper trade-off between the technology complexity and the relevance of support for the older users; on the other hand, it also suggests the requirement to personalize the support in relation to actual user needs.

### 2.1.2 The ExCITE project

The basic goal of ExCITE was to help develop a technology that could facilitate social interaction of potentially isolated people (in their home or in a health institution) to increase the level of social participation thus diminishing the sense of loneliness.

**The ExCITE technological ingredients.** The project exploited a remotely controlled robot, named Giraff (<http://www.giraff.org/>), able to move within the environment and endowed with a teleconferencing system (Figure 4).

Giraff is a remotely controlled mobile, human-height physical avatar integrated with a videoconferencing system (including a camera, display, speaker, and microphone).



**Figure 4:** The ExCITE project: testing a telepresence robot in ecological settings and with a long term perspective.

It is powered by motors that can propel and turn the device in any direction. The head unit can tilt and pan to simulate eye-to-eye contact using servo motors. The base moves using a differential drive movement system. A remote user can charge the Giraff by driving it onto docking station. The docking station charges the batteries in under 2 h. A full charge is sufficient to allow the Giraff to wander untethered for over 2 h.

The robot is operated by a person (i.e. a relative, a caregiver, or a friend), the *secondary user*, who wants to contact the senior, namely the *primary user* in his/her living environment (e.g. home, health care institution, etc.). The secondary user can drive the robot through the primary user's environment to reach different locations, by using a simple software installed on a computer. The ExCITE project was based on the idea of using a commercial robust robot to face the previously mentioned challenge of continuity of use. In this respect, no additional AI technology was tested within ecological settings. The intuitive idea in ExCITE was in fact to employ simple but robust technology, offering limited but consolidated functionalities, and to investigate possible problems/challenges that may arise from a deployment in real contexts.

**Long-term ecological experiments.** One of the original features of ExCITE consists of realizing long term experiments involving older adults hosting the robot in their living environment both to communicate with others and to receive assistance services. Figure 4 gives a general idea of the designed method to evaluate features over time. The evaluation entails a period of  $N$  months (with  $3 \leq N \leq 12$ ) during which the end user had the robot at home and the clients could visit him/her through it.

Assessment happened at milestones  $T_0$ . Specifically, after an initial assessment ( $T_0$  in figure) at the beginning

of the experimentation (*baseline*), the variables of interest are measured at regular intervals ( $T_1 - T_n$ ) to observe changes over time. At the last month, the Giraff was removed from the end user apartment and the same variables were assessed again after 2 months from this removal (*follow up*). The general idea was to use a repeated measures method to see changes over time during the long term usage of the robot. A detailed description of the evaluation protocol is provided in ref. [17].

Table 1 gives an overview of the primary users of the case study participants and the duration of the associated test site. In particular, eight primary users completed the long term assessment and, more specifically, three in Italy, three in Spain, and two in Sweden. Nine secondary users (aged 23–58 years,  $M = 42, 9, SD = 10, 2$ ; two females, seven males) participated in the long term study. Most of them lived in the same city of the primary user which they were connected to, except for one Italian and one Swedish secondary user. Three secondary users (two females and one male) worked as healthcare professionals and took on the role of formal caregivers. The others participants are represented mostly by family members – a grandson and four sons – and by a friend of one of the primary users.

We relied on the Almere model [18] that is specifically developed to test the *acceptance* of assistive social agents by older users. We studied, additionally, *Usability*, *Attitude*, *Telepresence* (*Social presence*, *Spatial Presence*, *Social Realism*, *Social Richness*), *Affective response*, and *Perceived social support*.

**Results.** Robotic acceptance for all test sites is either maintained or lowered. This is most likely tightly interlinked with expectations and also the diminished novelty of the unit over time and also to technical problems

may have influenced the changes over time. Overall, Giraff appeared to be a good means of communication that conveys a nice sense of warmth and intimacy for the older users. The tested people did not feel invaded their privacy by the Giraff presence and this is also confirmed over time. This means that the robot is generally not perceived as an element of intrusion in the old person's life.

The Giraff is quite appreciated by secondary users who have the role of caregiver (formal or informal). The expectations towards a system that may potentially provide a social assistance having a service or remote monitoring support role are confirmed during the users' long term experience. The robot, however, was also perceived as too limited and some additional functionalities were desired together with some further level of control. This is in line with the Acceptance Theory Model that claims that the acceptance of technology depends on the perceived usefulness. In this respect, it is important to produce technology that has the right compromise between utility but also simplicity of use and the right level of complexity to allow a natural interaction.

**Lessons learned.** Many of the aspects that have emerged in ROBOCARE have been further investigated in ExCITE. The project aimed at testing the concrete and continuous use of the system in real houses by taking into account both technical and social (human–robot [H–R] interaction) perspectives. This has the twofold advantage of allowing an examination of the use of technology in natural environments of use and for sufficiently long periods of time that allow us to observe variations due, for example, to the effect of habit or the growing familiarity acquired with the technology being studied.

**Table 1:** Primary user overview

Name	Age	Gender <sup>a</sup>	Education <sup>b</sup>	Tech use <sup>c</sup>	Secondary users	Duration (months)
Italy						
Case IT1	77	F	1	2	1 family member	17
Case IT2	65	M	2	1	1 family member	19
Case IT3	72	F	1	1	2 professional caregivers	19
Spain						
Case ES1	65	F	1	1	1 family member	27
Case ES2	80	M	1	1	1 professional caregiver	16
Case ES3	77	F	3	1	1 family member	14
Sweden						
Case SE1	72	F	3	1	1 family member	21
Case SE2	74	M	3	2	1 family member	7

<sup>a</sup>Female = F, male = M.

<sup>b</sup>Primary school = 1, secondary school = 2, high school = 3, university degree = 4, others = 5.

<sup>c</sup>Tech use refers to the frequency of technology usage with often = 1, sometimes = 2, never = 3.

This opens up an interesting perspective for developers, who can receive more concrete and contextualized feedback compared to fast tests carried out in a laboratory environment. At the same time, the study of the socio-psychological aspects of technology on people can exploit the advantage of a perspective of continued use over time. The role of AI becomes increasingly preponderant, requiring for the development of such a system a significant number of people with orthogonal skills.

The *Ecological long term experiments* able to reproduce as much as possible the actual conditions of use of robotic technology are paramount to assess the robustness and usefulness of technology.

**Shortcomings.** While the ecological long term experiments allowed us to gather valuable information related to the continuity of use, some shortcomings emerged regarding the perceptions of users towards the robot's capabilities. Primary users had higher expectations about the robot's abilities and the services offered by the technology. After an initial enthusiasm related to the novelty effect, they expressed the need to equip the robot with more useful services and a more proactive and engaging interaction. From this we can derive a further challenge:

The *intelligent and proactive behaviours* of robotic solutions are expected from older users. Technology should exhibit intelligence and usefulness in daily life situation to be judged as use-worthy.

### 2.1.3 The GIRAFFPLUS project

The GIRAFFPLUS project grounds its ideas on a more mature technology able to guarantee continuous operation and long term experimentation. The main aims of the project were as follows:

- to develop a complete system able to collect older people's daily behaviour and physiological measures from distributed sensors, to perform context recognition and long term trend analysis. Somehow the strong simplifications of the ExCITE project were mitigated reintegrating the idea of Intelligent Environment (similar to the RDE in ROBOCARE but with more mature technology);
- to organize the gathered information so as to provide customized services for both older adults and their caregivers;
- to assess in the long term the effectiveness of the services and the acceptance of technology in real settings.

**GIRAFFPLUS technological ingredients.** Figure 5 shows the general idea of the integrated system which is composed of a layer of sensors (*Sensor Network*) dedicated to the data acquisition from both the assisted person and the environment. These data are then processed by AI algorithms (*AI Data Interpretation*) to abstract more relevant information for monitoring people's routine, such as activity recognition or environmental monitoring, to detect possible dangerous situations. Interpreted data are then translated into user services (*Personalized Data Visualization and services*), bringing information in the right form to each category of users. The basic benefit pursued by the GIRAFFPLUS system is twofold: primary users can access the information on their own health condition, enabling them to better manage their health and lifestyle; they can receive *reminders* and *suggestions* as well as *visits* from friends and caregivers via *telepresence*. Secondary users are supported by a flexible and efficient *monitoring* tool that also provides *reports* and issues *alarms* in case of dangerous situation for their assisted person.

Figure 6 gives the general idea of the Data Visualization, Personalization, and Interaction module (DVPIS) that is responsible for the delivery of such services with two different modules: (a) an additional tool (DVPIS@Home) integrated in the robot at home which delivers additional information to the assisted person in the home environment and (b) a dedicated subsystem called DVPIS@Office for the broad class of secondary users. Both these modules are composed of a *back-end* part, devoted to organize the content of the information to be shown to the users, and a *front-end* part, responsible for presenting the information and services to the different categories of users.

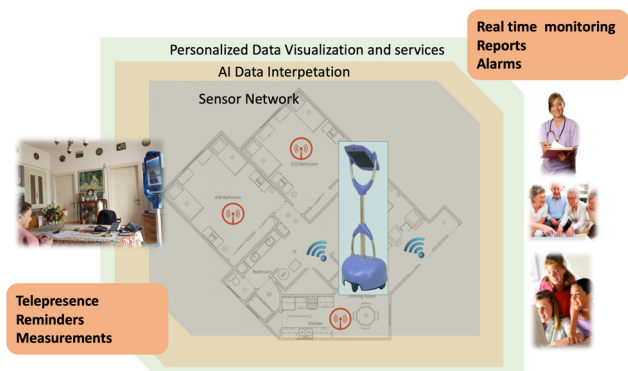


Figure 5: GIRAFFPLUS integrated system.

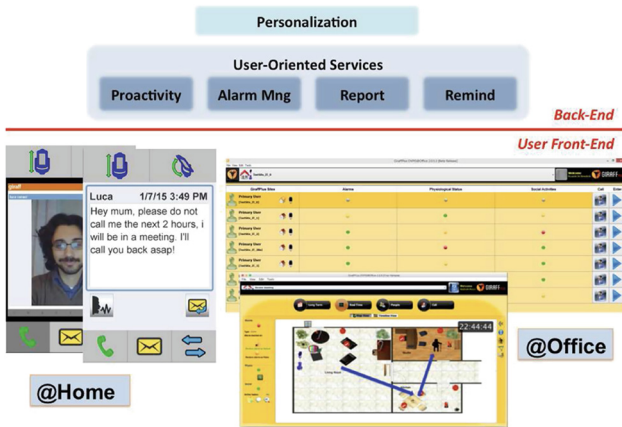


Figure 6: Personalized services for primary and secondary users.

**Services for primary users.** Services for the older adults have been conceived according to the ethical principle that the primary user as “data producer” should maintain a level of understanding and self-awareness on their health and should also have a means to keep in contact with the external world. The main services provided to primary users are therefore:

- **Avatar:** This functionality preserves the “traditional telepresence” service that the Giraff robot provides so that secondary users can visit the older user’s apartment through the telepresence robot.
- **Messages:** An additional environment has been added to allow the primary user to receive *messages* from secondary users or *reminders* and *suggestions*. Messages and reminders are provided in both textual and spoken form.
- **Shared data:** This environment allows us to show personal data to the primary user (e.g. physiological measures) and endows the system with a shared space between the primary user and the secondary users that could foster a discussion on the health status and habits of the old person. The general aim is to improve older adults’ awareness and also to encourage responsible behaviours for increasing their well-being.

It is worth highlighting the use of automated planning techniques for the administration of personalized and adaptive reminders [19]. Automated planning, in particular, is used to plan “virtuous paths,” to be followed by the primary users, to achieve certain objectives, determined by the secondary users, related to the primary users’ personal well-being.

Personalization, in particular, takes place taking into account both the current state of the user, inferred through

context analysis techniques, and, at the same time, the determined objectives. The result is a plan, characterized by a set of personalized stimuli that pursue one or more objectives. Finally, the execution of this plan takes the form of sending these stimuli by messages about food suggestions and healthy lifestyle hints, like specific seasonal vegetables and fruits or, in summer, advises about drinking water.

**Services for secondary users.** One of the most interesting aspects of services for secondary users is the possibility for Health Professionals to follow a list of homes (and consequently primary users) that have the GIRAFFPLUS system installed in their apartment. Specifically, the list of followed user contains a brief and immediate information on the status of the assisted person in terms of three main indicators: **Alarms**, **Physiological**, and **Social** aspects. For each of this dimension an immediate feedback is given with a judgment on the level of each indicator: *green = good*; *yellow = warning*; *red = risk*. In this way, a secondary user can easily judge if he/she needs to urgently intervene on some specific situations and in general he/she can modulate and prioritize the visit to the different patients, thanks to an immediate feedback without the need to entering into the details of each home. For each of these people, the secondary users can observe the real time view of the house on a map depicting sensors installed in the house; the physiological data specific for the patient; can also ask *daily/weekly or monthly report* for the main activities to observe possible deviations from routines. Another relevant service for secondary users is the implementation of a new panel dedicated to foster the discussion among the *network of persons* related to a primary user. Specifically, an environment has been developed where the different actors involved in the care of a primary user can exchange information and opinions so as to maximize the overall care for the old person at home.

**Long-term experiments.** Similarly to the ExCITE project, also this system has been tested in the long term. Specifically, 15 test sites were considered for 1 year of investigation focusing on the following dimensions: *Acceptance*, *Adoption and Domestication*, *PIADS*, and *Telepresence*. Overall, the perceived acceptance was maintained over time and the Adoption and Domestication dimension confirmed that users appreciated the system functionality and felt it could become a useful tool part of their daily routines. In support to this it is also worth saying that at the end of the experimentation in many cases we decided to leave the system in the home of the



experimenters, having also the need to define an “exit strategy” for the end of the experiment. This highlighted the need to have not only the technology but also the equipment of health professionals and care givers as enabling factor for the success of this kind of technology.

**Primary user results.** From the primary users’ perspective, older adults felt more protected having a monitoring system at home; they felt “more autonomous” and they felt they weighed less on their families. Older adults appreciated the ability to communicate via the robot yet they expected more manipulative capabilities and at the same time asked for additional features (e.g. voice commands). The issues related to privacy did not seem to be a problem even though in some cases the configuration of the sensor network was limited by privacy concerns. Some interest about costs also emerged and older adults expressed concern on who should pay for such a service.

**Secondary user results.** Family members were very interested in alarms and possible dangerous situations and they also appreciated the periodic report on the older adult’s routine. Doctors appreciated the possibility of routinely monitoring and correlating physiological data with lifestyle habits. Finally, doctors and formal caregivers saw GIRAFFPLUS as an aid to their work (e.g. they appreciated the possibility of monitoring multiple people at a distance, optimising real visits, and better managing false alarms).

**Lessons learned.** With the introduction of sensors experienced in GIRAFFPLUS, the need to interpret the data coming from them has immediately emerged. Even if only limited to the possibility of the robot to autonomously return to its charging base or to the ability to send personalized and contextualized messages to the users, more and more autonomy is required from the robotic platform. Also, the capability of providing end users with proactive assistance, “anticipating” their specific needs and habits emerged as a clear requirement in order to perceive the robot actually as an acting and “thinking” entity of the environment. In this regard, robot autonomy should deal with unpredictable and heterogeneous behaviours of end users to support “natural” and reliable interactions. Namely, robotic solutions should be aware of the *uncertainty* concerning H–R interactions and carry out (continuous) assistance in a robust way.

The *Robustness and reliability* of robotic solutions are crucial in daily-living scenarios. Technology should exhibit the level of autonomy needed to interact with users and environments in a *smooth* and continuous way.

The *Human-awareness* is crucial to realize robotic effective solutions that tightly interact with end-users. The autonomy level of a robot should take into account the possible dynamics of human users in order to guarantee robust and continuous assistance.

**Shortcomings.** A delicate aspect that had to be faced in the ecological and long term experimentation was related to the conclusion of the experiments and the consequent interruption of the supportive service. In fact, technology alone was not sufficient to guarantee the continuity of a service that inherently requires organizational support behind it to be functional and effective. This has highlighted a new challenge for system design like GIRAFFPLUS which are inherently *socio-technical* systems, which means that they act as enabling technology for new socio-health assistance models but they cannot disregard the human component.

Technology alone is not enough to provide better assistance but it is an enabling factor to optimize and renew the care and assistance systems which are *socio-technical systems*.

#### 2.1.4 SI-Robotics

As already briefly mentioned for the GIRAFFPLUS project another important aspect of the robotic support systems concerns the ability to serve different situations and scenarios by providing *modular* and *customizable* solutions.

This is what we are pursuing within the SI-ROBOTICS (Social ROBOTics for active and healthy ageing) project, whose aim is to design and develop novel solutions for socially assistive robots to support seniors in different contexts.

The objective is to propose novel AI-based robotic solutions realizing a variety of assistance services in different scenarios ranging from daily-home living (e.g. for continuous daily assistance) to hospitals (e.g. for health monitoring or rehabilitation support). The daily self-management of one’s own health, declined in activities such as following a correct diet, practicing constant physical and cognitive exercises and taking drugs adequately, often represents an important challenge for the older adults population, characterized by fragility, cognitive decline, or poor health and technological literacy. Personal robotic assistants, able to promote healthy lifestyles, characterized by an empathetic communication and reliability over time, can help solve this problem by adopting strategies that also aim to motivate the assisted persons.

**The SI-ROBOTICS technological ingredients.** Central to SI-ROBOTICS are *personalization* and *adaptation* which translate into the capability of contextualizing assistive services to the needs and “features” of different social and environmental contexts as well as health needs of assisted persons. The project aims at addressing these issues from both hardware and software perspectives. On one hand, it aims at realizing an innovative *modular* robotic platform that can be “easily” configured and adapted to different scenarios. On the other hand, the project aims at developing and integrating AI technologies to realize the cognitive capabilities a robot should be endowed with to autonomously *recognize* features and needs of different scenarios and consequently *decide* and *synthesize* effective “tailored” assistive services. The project grounds on an integration of different AI technologies, i.e. *machine learning* (ML) for long term and continuous adaptation, *automated planning* (AP) for flexible decision making, *knowledge representation & reasoning* (KR&R) for context awareness with the aim to support behaviour flexibility.

**Current results.** Research efforts have focused on the integration of ML, KR&R, and AP to support physical/cognitive rehabilitation scenarios [20,21]. Taking inspiration from dual-process theory [22], we have focused on the design of a novel cognitive architecture supporting the synthesis of personalized stimulation plans, administered through adaptive H–R dialogues. A feasibility study shows a demonstration of the pursued approach to model different needs and preferences of persons based on their health needs and provides examples of personalized stimulation and H–R interactions modulated according to the model.

More specifically, an ontological representation of the International Classification of Health, Disability, and Health (ICF – <https://www.who.int/classifications/icf/en/>) has been defined to model health needs of assisted persons and H–R interaction preferences. Knowledge reasoning mechanisms process user knowledge by inferring cognitive (or physical) impairments. According to the refined knowledge a set of tailored stimulation actions are identified and given as input to a planning engine, which is in charge of synthesizing a personalized stimulation plan.

Namely, a planner receives input knowledge characterizing the types of stimulation action that fit the needs of a patient together with a number of interaction parameters characterizing the way such actions should be executed. Personalized stimulation plans are then given to an ML reactive layer that encapsulates Natural Language

Understanding features to execute stimulation actions through dialogue-based interactions.

**Identified challenges.** The SI-ROBOTICS project pursues a more general perspective where a robotic system should support different types of end users in different types of scenarios enabling a *modular* and *personalized* support. The pursued approach is to integrate a number of AI technologies to endow the system with the cognitive capabilities needed to autonomously recognize the needs of assisted persons, the objectives of a specific scenario and adapt its behaviour accordingly. One of the main identified challenges is the synthesis of assistive systems endowed with the *intelligence* needed to contextualize their assistance according to the scenario and the users it interacts with. On one hand, *personalization* and *adaptation* concern the types of service users need in a particular context and health-related situation (i.e. *what* kind of assistance the system should provide). On other hand, these qualities concern the way such services should be carried out to “maximize” the efficacy of the assistance and *user acceptance* (i.e. *how* a robot should interact with users according to their features, interaction capabilities and preferences).

*Personalization and adaptation* of robot behaviours are paramount. General skills and assistive capabilities of robotic solutions should be tailored to the heterogeneous needs and interaction features of assisted end-users.

Another important challenge is also related to the safe deployment in real settings that may present different physical constraints:

The *Safety* of robot technologies should be considered when deploying them in real-world scenarios. Autonomous behaviours of a robot should be constrained according to the risks concerning the safety of human users.

Indeed, safety is particularly relevant in critical environments such as hospitals or the homes of fragile people.

## 2.2 Other contributions

The work and the results presented above are part of a wider state of the art constituted by important research advancements in designing and developing technological solutions, specifically tailored to foster Active and Healthy Ageing.

More in general, the “Active Assisted Living” (AAL) research area constitutes a field in which assistive tech-

nologies are exploited to implement services for older adults that can be classified into four main areas [23]: (1) AAL tools for physical impairments, (2) AAL technologies for cognitive impairments, (3) smart home technologies for physical and cognitive impairments, and (4) AAL technologies for social participation and reducing caregiver burden. The research projects presented in Section 2.1 clearly cover most of the AAL areas as they provide solutions as a set of integrated technologies to deal with cognitive impairments (Area 2), deployed in smart homes (Area 3), and fostering social interactions (Area 4).

Moreover, some of the barriers elicited in our projects are among the most relevant issues related to the use of Innovative Assistive Technologies by older populations. Indeed, the analysis of state of the art performed in refs. [23,24] highlights very limited experience for older adults in using advanced technologies, and a lack of motivation to participate in activities due to, e.g. physical or cognitive impairments. Therefore, the need for continuity of use, ecological long term experiments, and human-awareness pursuing multidisciplinary approaches are clearly crucial elements to develop robust, reliable, and acceptable AAL systems.

Furthermore, most of the proposed solutions consider a conceptual validation (not through evaluation processes), which suggests the lack of proper involvement of real users in all phases of development, and many AAL solutions were only tested in laboratory. There is also lack of research related to the caregivers' burden and their stress for taking care of older ones, as well as lack of evidence of clinical effectiveness of the proposed solutions [23]. More in general, the development of technological components has decreased through years compared to the development of systems that can be used by real users in different real-life scenarios. This is somehow in line with the AAL paradigm which foresees more complex systems to be included in ecological environments for improving human quality of life. This further reinforces the significance of challenges identified in Section 2 as there is still a high number of experimentations more focused on the development and implementation rather than the validation and evaluation of the efficacy of the AAL systems.

In order to present here a more comprehensive view of this field, we selected a significant representation of related works considering the list of research projects funded within the two main European funding schema, i.e. the most recent Research Framework Programmes (namely, the 7th Framework Programme FP7 and, the so called, Horizon 2020) and the AAL Joint Programme. Indeed, these two main programmes are implementing the biggest European research initiative for developing

ICT-based and robotics research projects for active and healthy ageing. Therefore, we selected the more relevant and significant funded projects considering all the AAL calls since 2008 and the following specific FP7 and Horizon 2020 calls.<sup>2</sup> We think that the projects funded within the aforementioned programmes represent a significant picture of the cutting-edge technologies and research initiatives in Assistive Robotics for older people. In the following, we selected the most effective and representative projects addressing a variety of research challenges that help in building a complete picture of the state of the art and further points to suggest opportunities for the future.

### 2.2.1 Robotic solutions for AAL

A large number of research initiatives are dedicated to develop and propose robotic solutions for AAL such as, e.g. SAR [25] or Robotic Socio-Ecological Systems [5]. The projects described in Section 2.1 contributed to the state of the art but, clearly, there are also other work/projects focused on addressing different aspects. Along the same line, several other research initiatives and projects investigated the integration of robotics and ambient intelligence solutions for supporting older adults living alone in different scenarios. There was a strong effort in this direction and here some representatives are presented just to mention few of them.

Robot-Era project [26] aimed to increase the acceptability improving the quality of robotic services proposing a cognitive-inspired robot learning architecture and using different platforms for indoor and outdoor applications. Its scope was to integrate robotics and ambient intelligence technologies, AI and cognitive-inspired robot learning architectures, elderly user-needs, methodology of design for acceptability, and legal/insurance regulations and standards fundamental for the real deployment. All these skills have been applied to generate robotic services for "ageing well" and to propose a set of appropriate solutions to overcome actual barriers to the exploitation of robotic services. The Robot-Era platforms were tested in realistic environments to

---

<sup>2</sup> FP7: ICT-2007.7.1 - ICT and ageing, ICT-2009.7.1 - ICT & Ageing, ICT-2011.5.4 - ICT for Ageing and Wellbeing, Horizon 2020: PHC-19-2014 - Advancing active and healthy ageing with ICT: service robotics within assisted living environments, SC1-PM-14-2016 EU-Japan cooperation on Novel ICT Robotics-based solutions for active and healthy ageing at home or in care facilities, DT-TDS-01-2019 Smart and healthy living at home.

evaluate their actual impact on acceptability with end users considering different application scenarios, i.e. domestic, condominium, health facilities, and public spaces.

ENRICH-ME [27] aimed to enhance the day-to-day experience of elderly people at home with technologies that enable health monitoring, complementary care, and social support. ENRICH-ME proposed a system composed of a companion robot deployed in a sensorized environment and a Networked Care Platform providing a set of remote monitoring services for healthcare professionals based on smart environments, human perception and advanced autonomous navigation technologies, and cognitive robot control. The system was evaluated in laboratory settings and, with a limited temporal deployment, also in some real environments.

Similarly, CompanionAble [28] addressed the issues of social inclusion and domestic care of older adults with mild cognitive impairments. The project focused on combining the strengths of a mobile robotic companion, called Hector, with the advantages of a stationary smart home. Hector was enriched with remote monitoring services, personalized dialogue/interaction displaying emotional intelligence to avoid feelings of loneliness, provide friendly reminders, store/bring important objects such as keys, wallet, and offer cognitive stimulation/games, as well seamless video connections to family and friends. The CompanionAble system was installed in a number of demonstration homes testing its functionalities.

Mobiserv project [29,30] developed an integrated and intelligent home environment for the provision of health, nutrition, and well-being services to older adults. The goal has been to develop and use up-to-date technology like a companion robot, smart home, and smart clothes in an intelligent and easy to use way to support independent living of older persons. Based on state of the art AI and robotics technologies, the Mobiserv robot companion was designed to offer cognitive support to users, offering reminders and suggestions to help them lead healthy and socially active lives. During some trials, users experienced the system for several hours with a researcher present to observe and initiate a dialogue. The Mobiserv system was then evaluated and validated in a realistic setting with target users spending a week in a smart home.

In GrowMeUp [31], the focus was on allowing elderly people to live for longer in their own environment without losing contact with their social circles, staying active either via teleconference or other social facilities provided within the system. GrowMeUp developed an affordable robotic platform capable of learning older person needs and habits over time to enhance existing

or build new services for compensating older person capability degradation and gradually adapting its interaction over time. The system provided several functionalities for end users based on *Behaviour and Emotional Understanding*, an *Intelligent Dialoguing* and *Personalized care*. The robotic platform was validated through the execution of nine use cases at participant end users and both older persons and caregivers found the robot useful and motivating towards a more independent and active life.

RAMCIP [32] aimed to develop a service robot, capable to assisting older persons in a wide range of daily activities, being at the same time an active promoter of the user's physical and mental health by deciding when and how of assisting the user. The RAMCIP robot comprized three major innovative aspects: cognitive functions based on advanced user and home environment modelling and monitoring, allowing the robot to decide when and how to assist the user; novel adaptive multimodal human-robot communication interfaces, with emphasis on empathetic communication and augmented reality displays; advanced, dextrous and safe robotic manipulation capabilities applied in service robots for assisted living environments.

The aforementioned projects share most of the lessons learned in our path and, thus, reinforce our findings setting them up as general points for developing assistive robotics solutions for elderly people.

### 2.2.2 Additional lessons learned

Going beyond these results, and in line with the classification proposed by ref. [23], some projects focused on physical impairments, with major attention to mobility issues. At the same time, there are examples of developmental processes whit incremental user involvement through years as, for example, the case of the DALI project [33] and the subsequent ACANTO project [34]. The first one aimed at developing a robotic cognitive walker (c-Walker) that can be taken to, or picked up at, the place to be visited, gently guiding the person around the building safely. The specificity of this device lies on being able to take corrective actions when the user comes across the type of busy area, obstacle, or incident they want to avoid. The second one, funded within the Horizon 2020 programme, represents the evolution of these efforts where the scientists put their efforts in refining the technology deeply relying on a user-centred design and designed longitudinal study to assess the clinical effectiveness of the developed device (the FriWalk) both on



physical and psychological well-being [35,36]. These two projects developed a low cost robotic platform capable of analysing end users' social network activities to understand the social context, implement proper interactions with humans, and endow the system with a recommendation system for user activities.

Robots supporting older adults in *maintaining their mobility and helping them to prevent falls* are crucial for prolonging independence and preserve autonomy.

A further, and different, aspect addressed in some work concerns emotions. Indeed, emotions are included among the crucial interaction components for a socially interactive robot [37]. Therefore, social robots can be used to encourage emotional expression in situations where it may be challenging. So, for instance, robots are used to encourage children with autism to open up emotionally [38] and empathy is considered as relevant in providing assistance to elderly people [39,40]. With older adults, emotion constitutes a highly relevant human factor to take into account to improve user engagement while interacting with assistive robots. On one hand, psychologists showed that empathy plays a key role for therapeutic improvement and their assumption is that empathy mediates pro-social behaviour (see, e.g. ref. [41]). Patients who have received empathy from their therapist recovered faster and the same seems to hold with assistive robots. Robots can be designed to show empathy to improve user satisfaction and motivation to get better as well as enhance adherence to therapy programmes in the context of patient–therapist interaction [40]. The work in ref. [42] presents a prototype for an emoting robot that can detect emotions in one modality, specifically in the content of speech, and then express them in another modality, specifically through gestures. The robot is able to detect and express emotions through an emoting system. Results from a human validation study show people perceiving the robot gestures as expressing the emotions in the speech content. Additionally, people's perceptions of the accuracy of emotion expression are significantly effective. In ref. [43], an effective reasoning system has been implemented in the NAO robot for simulating empathic behaviours in the context of AAL. In particular, the robot recognizes the emotion of the user by analysing communicative signals extracted from speech and facial expressions. The recognized emotion allows triggering the robot's affective state and, consequently, the most appropriate empathic behaviour. The robot's empathic behaviours have been evaluated both by experts in communication and through a user study aimed at

assessing the perception and interpretation of empathy by old users.

The MARIO project [44] aims to help people with dementia by enabling them to stay socially active using touch, verbal, and visual H–R interaction tools. A unique capability of this effort is the ability to engage users with dementia in reminiscing about their past as well as people and places with emotional significance. Such reminiscing approach is well suited with mild cognitive impaired people to overcome communicative barriers and promote social interactions. The key objectives of MARIO were to address loneliness, isolation, and dementia in older persons through multifaceted interventions delivered by service robots, conduct near project length interaction with end users, and assist caregivers and physicians in conducting comprehensive geriatric assessments. Machine learning techniques and semantic analysis supported language, space, and mood recognition making MARIO more personable, useful, and accepted by end users. An assessment of deployment of MARIO robots was performed to provide evidence related to the benefits/impacts of the use of service (companion) robots involving a number of elderly people with dementia and their caregivers within three different environments, i.e. nursing home, hospital, and community and showing a good impact in terms of acceptance, engagement.

On this aspect, it is worth also mentioning efforts made to foster elder motivation in using technology, which has been noted to be a pretty hard challenge in the developing design. It can be the case of the HOBBIT project [45], more oriented to foster the interaction with the robot, whose core zoomed in on the interaction between robot and owner/user through a more user-centred concept called *Mutual Care*. This project allows and entices people to “take care” of the robot like a partner, so they can develop real feelings and affections towards it. The underlying idea is that, for people, it is easier to accept assistance from a robot when themselves can also assist the machine. Moreover, HOBBIT underwent an iterative assessment process from laboratory setting to ecological environment. The preliminary evaluation sessions in laboratory setting focused on the assessment on perceived usability, acceptance, and affordability of the robot and demonstrated a positive reception of the robot from its target user group [46]. Nevertheless, findings from a long term study show that the robot was rather seen as a toy instead of being supportive for independent living, despite utility met the user's expectations [47]. To summarize, the above work considers emotions, empathy, feelings, and affections as

relevant features that, as in human-to-human interactions, can play a key role in healthcare activities for older adults.

Designing robots capable of detecting and expressing emotions and showing empathy allows to deploy engaging robots and support therapy adherence.

Finally, some work is in progress to develop robots capable of adapting their behaviour according to different cultures. According to the *cultural competence* concept, i.e. the ability to respond effectively to people from different cultures and backgrounds, solutions can be developed to assist healthcare professionals in the delivery of services that meet cultural and communication needs of patients [48]. Under this perspective, culturally competent robots are to autonomously reconfigure their way of interacting with a user in a way that is appropriate to the culture and preferences of the person they are assisting. Though relevant, this concept has been rarely implemented and evaluated within robotics despite its importance for enhancing patient-centred care. Such abstract concept is implemented, e.g. in ref. [49]. This research project (funded under an EU–Japan cooperation programme for developing advanced robot-based solutions for extending active and healthy ageing and evaluating such solutions under different cultural perspectives) aims at designing, developing, and evaluating culturally competent robots that can assist older people according to the culture of the individual they are supporting. In CARESSES, socially assistive robots are configured to assist older adults residing in long term care homes in a culturally competent manner [50]. Robots understand which culture the user primarily identifies with and leverages a relevant cultural knowledge database to adapt its interaction behaviour. The robot uses this database (a hierarchically structured ontology) as a basis of its verbal and non-verbal interactions but then adapts its understanding of the user’s individual preferences and values as it receives feedback from the user during an interaction. Users may be more likely to accept and value interactions with culturally competent robots. This is important given how critical user acceptance is for the successful implementation of any public health intervention.

Culturally competent robots can configure their way of interacting with users according to their culture and preferences.

As summarized in Table 2, the projects presented above represent a wide amount of work considering many different AI and robotics technologies and solutions,

**Table 2:** Summary from related projects with explicit reference to AI and robotics technologies

Project	References	Main AI and robotics technologies
Robot-ERA	[26]	Ambient intelligence, knowledge representation and reasoning, automated planning
EnrichME	[27]	Smart environments, human perception, advanced autonomous navigation, and cognitive control
CompanionAble	[28]	Natural language processing and ambient intelligence
Mobiserv	[29]	Ambient intelligence, pattern recognition, and cognitive game stimulation
GrowMeUP	[31]	Intelligent dialogue system, machine learning, and knowledge representation and reasoning
RAMCIP	[32]	Machine learning, knowledge representation and reasoning, and ambient intelligence
DALI/ACANTO	[33,34]	Advanced autonomous navigation recommender system, and social context detection
Emotional and empathic robots	[38,40,41,43]	Emotion detection, affective reasoning, and multimodal interactions
MARIO	[44]	Machine learning, semantic analysis,
HOBBIT	[45–47]	Advanced autonomous navigation, human/gesture recognition, and task reasoning
CARESSES	[49,50]	Knowledge representation and reasoning, emotion recognition, and social signals

from knowledge representation to advanced autonomous navigation, to address several challenging issues related to fostering the diffusion of socially assistive robots. Most of the technologies often present some limitations. This is mainly due to the fact that such solutions have been often deployed as robotic prototype tested and evaluated in controlled environments for a limited period of time. Apart some very specific cases, the main challenge remains

in developing reliable solutions capable of supporting long term use in real scenarios.

### 2.3 Synthesis of lessons learned

After having presented an overview of our results and an analysis of the state of the art of works similar to our experiences, Table 3 summarizes what we believe are the fundamental characteristics for the successful development of the use of intelligent systems to support older people. In particular, the table summarizes the key features we derived from our analysis, the source from which they emerged, and a description of each feature.

The presented list may not be exhaustive, but in our opinion these characteristics are the main ones to increase the acceptance of the technology and its correspondence to the real needs of the user.

## 3 Directions for the future

In this section, we elaborate on the outcomes of the analysis summarized in Table 3 by reasoning on the emerged *features* and highlighting a set of related research challenges. Specifically, this section discusses the key technological and methodological aspects that are crucial for an effective deployment of future assistive robotic solutions.

**Multidisciplinary.** Our research path and the discussed related works characterize a trend that sees the research community moving from “simple” robotic systems endowed with some kind of autonomy and *intelligence* to increasingly complex *socio-technical systems*. Current research efforts indeed aim at realizing ecological systems (and not just “intelligent robots”) capable of symbiotically living and coexisting with one or a multitude of *human users* in a variety of *social contexts* ranging from domestic to public environments and structures. A synergetic integration of contributions and methodologies coming from different research areas and fields are therefore essential to realize solutions that are valid and effective from technical, assistive, and social perspectives. A paramount *requirement* that clearly emerged from our analysis and that constitute a *pillar* of any future work in this area is *multidisciplinarity*.

**A threefold perspective.** A multidisciplinary approach entails the capabilities of taking into account different and potentially conflicting *perspectives* when designing SAR systems and assistive services. Taking into account the outcomes summarized in Table 3, we particularly consider three perspectives as crucial: (i) *technological*, (ii) *socio-health*, and (iii) *human*.

The *technological perspective* is clearly central since the realization of such artificial systems capable of interacting with humans in ecological environments raise several non-trivial technical challenges. As pointed out in Table 3 indeed technology should be mature enough to guarantee qualities such as *continuity of use*, *robustness and reliability*, and *safety*. The *socio-health perspective* is important to “model” the behaviours and overall functioning of such system in a way that is correct, useful, and valid with respect to the assistive scenarios. This perspective characterizes features such as *intelligent and proactive behaviours*, *personalization and adaptation*, and *physical support* that define *how* an SAR system should behave in a particular assistive scenario/context. This perspective is for example crucial to determine which kind of “health parameter” should be monitored, which kind of “health-related event/situation” should be detected, and how the system should proactively support primary and secondary users (i.e. respectively assisted persons and doctors/caregivers). Finally, the *human perspective* is necessary to characterize behaviours that are “socially-acceptable” and coherent with the implicit/explicit expectations of end users. Features such as *cultural-awareness* and *emotional-awareness* are indeed crucial to endow SAR systems with *behavioural rules* that allow adapting the way assistance is carried out according to for example the current emotional state of the assisted person or to the *social norms* expected in the considered scenario. These aspects are strictly connected to *user experience* and necessary to realize SAR systems that co-exist with humans by behaving and interacting with them in a human-like (or *human-aware*) way.

**Joint research efforts.** Each *perspective* entails the integration of contributions from different and heterogeneous *research fields* to satisfy functional and non-functional requirements. In our opinion, the effective achievement and implementation of the features highlighted in Table 3 are subordinated to the effective integration of technologies and methodologies coming from: (i) Robotics, (ii) AI, (iii) ICT, (iv) Health, and (v) Social science.

**Table 3:** Discussion of lessons learned from projects

Source	Features	Description
ROBOCARE	Continuity of use	System robustness and continuity of use are paramount to offer helpful services over time that adapt and, if possible, update with the environment.
	Multidisciplinarity	The integration of competences from different disciplines, such as AI, Robotics, Psychology, Gerontology, H–R interaction, Health, is needed to build effective and accepted solutions.
ExCITE	Ecological long term assessment	Long-term H–R interaction studies in the real-world are needed to improve the understanding of how people respond to robots in complex social contexts and how robots influence social dynamics [51].
	Intelligent and proactive behaviours	Older adults expect intelligent and proactive behaviours from robotic assistants. Like all the intelligent agents, systems supporting older adults also analyse data from sensors, perform some forms of automated reasoning, and contextually, generate actions towards users. Forms of intelligent reasoning are particularly useful to recognize anomalies and to generate messages related to relevant aspects of the older adults’ lives (e.g. alerts, reminding, coaching, or statistics, for health professionals).
GIRAFFPLUS	Robustness and reliability	The introduction of assistive systems in ecological environments brings a significant number of challenges ranging from possible Internet connection problems to the interaction of the robot wheels with potential carpets or stairs, from the interferences that glasses and mirrors may have with distance lasers to the physical installation of environmental sensors in a house with their intrinsic power and connection problems. All these aspects can affect the robustness and, therefore, the effectiveness of the resulting systems, both in the short and in the long term.
	Human awareness	Assistive solutions should be built around end users and thus be able to support them in a variety of scenarios according to their specific needs and preferences. Assistive robots and related services should show some degree of flexibility to adapt services and the way they are carried out to the (heterogeneous) needs of older adults. Co-existence and interactions between the assistive technology and the end user should be as much natural as possible, limiting the impact to the habits and the daily-home living of older adults.
	Socio-technical system	AI and robotics are enabling technology to provide more effective assistance to older adults, but they cannot substitute the human component. The intelligent systems should in fact be seen as socio-technical systems in which the two actors (technology and human) cooperate according to their respective competences to guarantee continuous support and help also optimizing the human resources.
SI-ROBOTICS	Safety	Autonomous robots should be capable of <i>evaluating</i> risks concerning the interaction with end users. Robot controllers should constrain behaviours to avoid direct or indirect risks to the health of end users. In addition, end users should maintain some level of control over robotic technologies (e.g. stop or slow-down robot motions if they perceive some danger).
	Personalization and adaptation	As each user has her/his own needs and requirements, the systems must be carefully tailored to people, dynamically adapting to changes that can occur at different time scales.
OTHER EXPERIENCES	Cultural-awareness	Robot should adapt the way they interact with users according to preferences, habits, and expectations <i>inherited</i> from the considered cultural context.
	Physical support	Robots supporting older adults in maintaining their mobility and helping them to prevent falls are crucial for prolonging independence and preserve autonomy.
	Emotional-awareness	The design of robots capable of “understanding” emotions as well as detecting and showing empathy is crucial to improve therapy adherence through engage interactions.

A tight integration of AI and robotics is central to the realization of effective solutions. On one hand, robotics

constitutes the hardware and software “layers” that are crucial to realize reliable, safe, and autonomous behaviours



of robotic devices that physically interact with human users and the environment. On the other hand, AI constitutes the enhanced software layers that would endow robots with the cognitive capabilities needed to enhance the flexibility of robot behaviours as well as adapt and contextualize robot behaviours to the different assistive contexts. In particular, we see AI technologies and methodologies as a key integration and harmonization point of the heterogeneous requirements coming from the considered perspectives. AI therefore plays a key role in pursuing the view of SAR systems as complex integrated *holistic* systems.

ICT is crucial to enrich assistive robots with increasingly advanced and reliable perception capabilities through sensors and/or increase computational capabilities of robotics solutions through the integration of cloud services, when possible. Such technologies are particularly relevant to achieve a distributed approach and thus delocalize the “embodiment” of perception and reasoning capabilities of AI-based robots. For example, the integration of environment sensors allow a system to *perceive* the whole environment and not just the area surrounding the robotic platform.

The integration of AI with Social Science and Health is crucial to take into account the “domain expert” at different levels and thus synthesize robot behaviours and assistive services that are effective. Contributions

from Health enrich AI services with the knowledge and procedures necessary to properly interpret for example physiological data and identify critical health conditions and situations. Additionally, it enriches AI services with the knowledge necessary to personalize assistance according to the specific needs of end users. Contributions from Social Science instead enrich AI services with human-level knowledge necessary to carry out behaviours that are compliant with social norms that are “relevant” in the different assistive scenarios [52,53].

**A recipe for future SAR systems.** Our “recipe” for the next generation of SAR systems is summarized in Figure 7. The features of Table 3 are grouped into the discussed perspectives, pointing out the needed synergies among research fields. The left side of the figure characterizes the *technological perspective* and depicts the needed interactions among robotics, AI, and ICT to properly support technological features such as *continuity of use, safety, robustness and reliability*. The right side characterizes the *socio-health perspective* and points out the needed interactions among AI, robotics, and Health to properly support features such as *intelligent and proactive behaviour and personalization, and adaptation*. A mutual contribution of these research fields is essential to exhibit behaviours that are effective and correct with respect to *socio-health assistive objectives*. The bottom side then

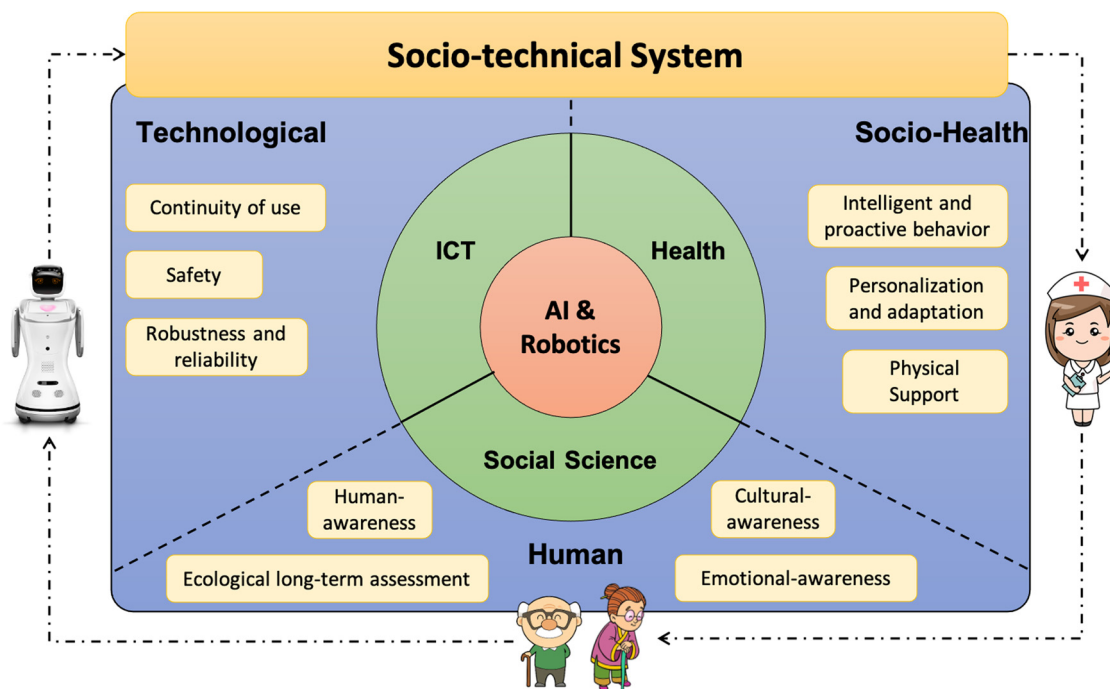


Figure 7: Multidisciplinary approach to robotic assistance.

characterizes the *human perspective* and points out the needed interactions among AI, robotics and Social Science. The contribution of Social Science is indeed crucial to foster the development of “human-aware” and *trustworthy* AI technologies and effectively deal with social interaction dynamics.

In our opinion, these aspects are indeed key elements for a successful development and deployment of effective and acceptable intelligent agents in real life. Next sections specifically focus on some challenges we plan to address in the future and that are particularly relevant with respect to the mutual contribution of the discussed research areas.

### 3.1 Integrated AI and robotics

AI can endow robots with a significant number of *cognitive capabilities* ranging from *environment perception* and *knowledge representation* to *decision making* and *problem solving*. This allows the development of AI features in robotics capable of “playing” the central role envisaged in Figure 1. The integration of different AI technologies and their embedding in robotic systems are therefore central to the realization of effective assistance. Single AI technologies can support one or more of the needed capabilities but they cannot constitute a “master algorithm” capable of effectively dealing with all of them [54].

**Pushing integration.** Research in Cognitive Architectures has generally investigated the integration of different *cognitive capabilities* in a uniform approach with the aim of “replicating” and/or studying the functioning of the mind [55–57]. Conversely, research in AI has been characterized by a “vertical” development, generally focused on the study of single technologies with the aim to develop a specific intelligent functionality. Contributions from Cognitive Architectures (and more in general from Cognitive Sciences) can therefore strongly help AI in pursuing an integrated approach to the synthesis of *intelligent behaviours* [58]. AI techniques such as *knowledge representation* and *reasoning*, *machine learning*, and *automated planning* can effectively support *data interpretation and processing*, *flexible control*, and *adaptive decision making*. Additionally, assistive robots should be endowed with capabilities such as e.g. *user modeling* and domain knowledge representation to carry out *contextual reasoning*. A proper representation and processing of *knowledge* is crucial to support *situation awareness*, *adaptive decision making* and allow robots to autonomously *reason about goals*

and achieve them by interacting in a *socially compliant way* with end users. It is therefore necessary to propose novel AI and robotics integration schemes [59,60] enabling the interaction of a number of heterogeneous modules that work at different levels of abstraction.

**Perception and knowledge abstraction.** Regardless of the application domain, the capability of a robotic system to autonomously *act* in an environment, performing complex actions and interactions, strongly relies on *perception*. Perception is crucial to elaborate sensory data and thus gather the environmental information necessary to understand the current state of the *world* and monitor its evolution.

In general, there is a variety of information and consequently *knowledge* that can be extracted from sensing. According to the features of the available sensing devices, there can be a variety of intelligent techniques that can be considered for realizing reliable and effective information abstraction processes. Knowledge can then be further enriched by taking into account environmental as well as contextual information (e.g. the structure and known properties of the environment or the physical features of the objects and entities data refer to).

The knowledge obtained by perception processes is typically represented as symbolic information that is continuously kept updated and consistent as new incoming sensory data are perceived and processed (*knowledge maintenance*). It is at this level of abstraction that symbolic automatic reasoning techniques perform at their best. Ontological reasoning, in particular, allows robots to extract further and increasingly complex information taking into account general properties and relationships of a *known* domain [61–63].

A similar type of knowledge can be used for the automatic generation, through automated planning techniques, of the actions that an intelligent system should execute, through its actuators, to interact with the environment and achieve desired assistive objectives [64]. The combination of perception, ontological reasoning, and automated planning techniques, in particular, allows the system to have a high-level view of what is dynamically happening in the environment, guaranteeing, thanks to the planner’s predictive skills, the choice of the best actions to perform [65].

**Combining symbolic and subsymbolic approaches.** A last aspect worth to be mentioned concerns the actual execution of the symbolic actions which, once again, translates into a sequence of lower level instructions. In particular, intelligent techniques e.g. Reinforcement

Learning [66] can realize flexible robot controllers that implement robot motions by dynamically “tuning” robot engine parameters (e.g. voltages of robot motors). At the same time, following similar approaches, audio/video messages are generated for the user and various kinds of information are sent through the different available modes.

The introduction of an execution system allows us to quickly *react* to the small changes that dynamically occur in the environment, locally avoiding, whenever possible, expensive ontology updating, and/or replanning operations. It is worth noting, indeed, that the concurrent exploitation of symbolic and subsymbolic forms of reasoning allows the system to explicate high-level human knowledge (and, therefore, more easily formalizable), instantiating more complex yet broader forms of reasoning, while maintaining a connection with the contextual reality, which is simpler yet more responsive.

### 3.2 Transdisciplinary efforts

Figure 1 shows the synergy among different disciplines and shows a multidisciplinary approach to the implementation of assistive systems. In reality, the analysis carried out leads us to suggest a broader perspective and to promote the transdisciplinary approach [67] as a winning one. Indeed, both the interdisciplinary and the multidisciplinary dimensions may be too restrictive and limited.

Considering a broader perspective, “*Transdisciplinarity is an action-oriented approach where research questions emerge through consultation and interaction among several disciplines and sectors to develop socially useful, feasible, practical, effective, and sustainable solutions. In transdisciplinary research, societal real-world needs define the problem area, which in turn dictates which stakeholders need to work together. As such, transdisciplinary research provides an opportunity for transformative solutions in society by executing innovative projects that push through boundaries to impact both established and novel audiences and applications* [67].” Within this perspective, the efforts carried out through the years follow the principles belonging to the transdisciplinary approach exposed in ref. [67], namely, *Complexity and holism, Relationship, Communication, and Transformation*.

According to the just proposed perspective, the close interactions between researchers from different extraction and users foster the achievement of outcomes with

a transformative, real-world impact obtained, thanks to efforts carried out through an approach that considers all the involved stakeholders.

Transdisciplinarity represents indeed a challenge towards which research in AI and robotics for assistive purpose should point to. Among others, the interaction between ICT and Social Sciences is particularly crucial to endow robotics, through AI, with *socially compliant behaviours*. The capability of properly representing, reasoning, and interpreting *social dynamics* is crucial to adapt robot behaviours to different social contexts (e.g. public environments like hospitals or private environments like houses) as well as to user intentions and expectations. When humans and robots continuously interact in common-life scenarios, it is crucial to reason on *how* robot behaviours should be carried out to be *acceptable* from a *human perspective* [68]. For example, the capability of representing and reasoning about *social norms* is crucial to recognize and “filter” robot behaviours that, although technically feasible, would not be correct from a social perspective [69,70]. Similarly, the capability of representing and reasoning about the *mental model* of a user (Theory of Mind) would allow robots to better interpret user *expectations* and *intentions* and thus strongly improve the quality of interactions by anticipating user behaviours or properly interpreting potentially ambiguous instructions [71–73].

Also ethical issues represent an aspect which is receiving increasing attention and that should be considered as fundamental in designing and developing assistive technology for older people. This represents a crucial aspect, especially considering the frailty of the addressed target.

With specific regard to the usage of social robots with elderly care, six main ethical concerns have been identified by ref. [74], which may risk to become serious if not properly addressed. *Reduced human contact*: opportunities for human social contact could be reduced, and elderly people could be more neglected by society and their families than before. *Increased feelings of objectification and loss of control*: an insensitive use of robots developed for the convenience of carers might lead to a consequent increase in elderly people’s feelings of objectification and loss of control. This could occur if, for instance, robots were used to lift or move people around, without consulting them. *Loss of privacy and restriction of personal liberty* could also result from the use of robots with older adults who risk to be limited in their behaviours. *The deception and infantilization* of elderly people that might result from encouraging them to interact with robots as if they were companions, even if they do not

feel comfortable with it. Finally, there are issues about *responsibility* if things were to go wrong and this opens up other important issues such as the extent to which the wishes of the elderly person should be followed, and the relationship between the amount of control given to the elderly person, and their state of mind. Under a transdisciplinary perspective, beside the role played by experts who could help in embracing these principles, a fundamental way to deal with ethical issues requires pursuing a massive involvement of end users in the process of design and development of technological solution, letting all stakeholders in aged care, especially care recipients, have a voice in the ethical debate [75].

### 3.3 Socio-technical systems

The design of autonomous systems that provide fragile persons with continuous and personalized assistance is a complex task requiring joint efforts from multiple and heterogeneous research fields. The successful deployment of such systems in social situations is not just a technical issue. Doing things right and efficiently indeed does not guarantee user acceptance. Rather, it is important to allow robots to do right things in the right way. The transformative impact mentioned in the previous section can be effective just if it becomes clear that the co-existence of robots and humans in daily-living scenarios represents a complex ecosystem which would require a brand new assistive model. Indeed, an AAL ecosystem should be conceived as a socio-technical system composed of healthcare organizations, service provider professionals, customers, citizens, patients, infrastructures, technology-mediated platforms for communication, and industrial companies providing their products and services, which ensure value and services in a collaborative manner. For this reason, it becomes crucial to consider some key factors such as the governance policies and regulation, funding model, technology infrastructure, services, and stakeholders as part of a unique ecosystem. Indeed, socio-technical refers to the inter-relatedness of social and technical aspects of an organization or the society as a whole. Nevertheless, this path is still full of challenges which come sides. On one hand, people are still suspicious towards technology, at least as first impression before having used it. In robotics, there is evidence instead that acceptance and trust on technology increased over time when persons gained experience with a robot and became familiar with it (i.e. ref. [76]).

Moreover, with specific regard to AAL ecosystems, where also the healthcare system is involved, there is an additional challenge to face. In fact, there is still strong resistance to conceive a radical change of current healthcare models, which should be remodulated to integrate technology as a collaborative component instead of considering it as a mere additional support. In fact, embracing a socio-technical approach, healthcare service provision would require a renovation to integrate the technology in the current practice.

Summarizing, the key elements of the socio-technical approach would include combining human elements and technical systems together to enable new possibilities for an innovative assistive model where both technology, people and tertiary stakeholders make a step towards each other.

## 4 Conclusions

In this article, we have described a research and development path of intelligent systems that integrate AI and robotics, highlighting the challenges faced over the years and summarizing a list of crucial features that these systems exposed to effectively function in the long term in real contexts. The analysis has been enriched by the examination of similar works and by highlighting some challenges that are still to be resolved as well as promising lines of research for the future. Among these, we mention the integration of complementary skills and techniques, especially in reference to robotics and AI, the *transdisciplinary* approach and the vision of *socio-technical* integrated systems in which the human and technological component merge into a single system each offering its own synergistic contribution.

**Acknowledgements:** The article describes several projects the authors have been working at over the years. It is inevitable to express our gratitude towards the consortium members of the various projects. We would like also to thank specific colleagues who contributed to some of the results described in this article. More specifically: Riccardo Rasconi and Federico Pecora for their contribution to the development of the ROBOCARE system; Lorenza Tiberio, for her work on long-term experimentation in the ExCITE project; Luca Coraci and Giulio Bernardi for the development of user interaction modules in GIRAFFPLUS and finally Dr. Marcello Turno for his guidance and supervision on the medical aspects in the design of GIRAFFPLUS and in the relative experimentation with old users.



**Funding information:** The authors would acknowledge the support from several funding agencies, i.e. AAL JP programme, European Commission under the FP7 and H2020 programmes, Italian MIUR. At present, the authors are partially supported by the Italian “Ministero dell’Università e della Ricerca” under the project “SI-ROBOTICS: SocIal ROBOTICS for active and healthy ageing” (PON 676 – Ricerca e Innovazione 2014-2020-G.A. ARS01\_01120) and by CNR under FOE\_2020 Strategic Project “Technologies to support the most vulnerable groups: young and old – CLEVERNESS.”

**Author contributions:** Conceptualization: all authors; funding acquisition: Amedeo Cesta, Gabriella Cortellessa and Andrea Orlandini; methodology: all authors; project administration: Amedeo Cesta, Gabriella Cortellessa and Andrea Orlandini; software: Riccardo De Benedictis and Alessandro Umbrico; supervision: Amedeo Cesta; Visualization: all authors; writing – original draft: Gabriella Cortellessa, Riccardo De Benedictis, Francesca Fracasso, Andrea Orlandini and Alessandro Umbrico; writing – review & editing: all authors.

**Conflict of interest:** Authors state no conflict of interest.

**Data availability statement:** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## References

- [1] European Commission. Directorate-General for Economic and Financial Affairs and Economic Policy Committee of the European Communities, *The 2018 Ageing Report: Underlying Assumptions and Projection Methodologies*, Luxembourg: Publications Office of the European Union, 2017.
- [2] K. Marek and M. Rantz, “A new model for long-term care,” *Nurs. Adm. Q.*, vol. 3, no. 24, pp. 1–11, 2000.
- [3] J. M. Beer and O. L. Owens, “10 - social agents for aging-in-place: A focus on health education and communication,” in *Aging, Technology and Health*, R. Pak and A. C. McLaughlin, Eds., San Diego: Academic Press, 2018, pp. 237–259.
- [4] Consilium Research & Consultancy. “Scoping study on the emerging use of Artificial Intelligence (AI) and robotics in social care,” Technical Report, Skills for Care, 2020.
- [5] G. Mois and J. M. Beer, “The role of healthcare robotics in providing support to older adults: a socio-ecological perspective,” *Current Geriatrics Reports*, 2020.
- [6] N. Muscettola, P. Pandurang Nayak, B. Pell, and B. C. Williams, “Remote agent: to boldly go where no AI system has gone before,” *Artif. Intell.*, vol. 103, no. 1–2, pp. 5–47, 1998.
- [7] M. E. Pollack, “Intelligent technology for an ageing population: The use of AI to assist elders with cognitive impairment,” *AI Magazine*, vol. 26, no. 2, pp. 9–24, Jun. 2005.
- [8] T. Herrmann, M. Prilla, and A. Nolte, “Socio-technical process design – the case of coordinated service delivery for elderly people,” in *Blurring the Boundaries Through Digital Innovation*, F. D’Ascenzo, M. Magni, A. Lazazzara, and S. Za, Eds., Cham: Springer International Publishing, 2016, pp. 217–229.
- [9] A. Cesta, G. Cortellessa, R. Rasconi, F. Pecora, M. Scopelliti, and L. Tiberio, “Monitoring elderly people with the robocare domestic environment: Interaction synthesis and user evaluation,” *Comput. Intell.*, vol. 27, no. 1, pp. 60–82, 2011.
- [10] A. Cesta, L. Iocchi, G. R. Leone, D. Nardi, F. Pecora, and R. Rasconi, “Robotic, sensory and problem-solving ingredients for the future home,” in *Intelligent Environments: Methods, Algorithms and Applications*, Springer-Verlag London Limited, 2009, pp. 69–89.
- [11] A. Farinelli, G. Grisetti, and L. Iocchi, “Design and implementation of modular software for programming mobile robots,” *Int. J. Adv. Robot. Syst.*, vol. 3, no. 1, pp. 37–42, March 2006.
- [12] G. Grisetti, C. Stachniss, and W. Burgard, “Improving grid-based SLAM with Rao-Blackwellized particle filters by adaptive proposals and selective resampling,” in *Proceedings of the IEEE International Conference on Robotics & Automation (ICRA)*, 2005.
- [13] B. Pellom and K. Hacioglu, “Sonic: The University of Colorado continuous speech recognizer,” Technical Report TR-CSLR-2001-01, University of Colorado, published 2001/3/2.
- [14] A. Cesta, G. Cortellessa, M. V. Giuliani, F. Pecora, M. Scopelliti, and L. Tiberio, “Psychological implications of domestic assistive technology for the elderly,” *PsychNol. J.*, vol. 5, no. 3, pp. 229–252, 2007.
- [15] A. Cesta, G. Cortellessa, M. V. Giuliani, F. Pecora, R. Rasconi, M. Scopelliti, et al., “Proactive assistive technology: An empirical study,” in *Human-Computer Interaction – INTERACT 2007*, C. Baranauskas, P. Palanque, J. Abascal, and S. D. J. Barbosa, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 255–268.
- [16] V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis, “User acceptance of information technology: Toward a unified view,” *MIS Quarter.*, vol. 27, no. 3, pp. 425–478, 2003.
- [17] A. Cesta, G. Cortellessa, A. Orlandini, and L. Tiberio, “Long-term evaluation of a telepresence robot for the elderly: Methodology and ecological case study,” *Int. J. Soc. Robot.*, vol. 8, no. 3, pp. 421–441, 2016.
- [18] M. Heerink, B. J. A. Kröse, V. Evers, and B. J. Wielinga, “Assessing acceptance of assistive social agent technology by older adults: The Almere model,” *Int. J. Soc. Robot.*, vol. 2, no. 4, pp. 361–375, 2010.
- [19] R. De Benedictis, A. Cesta, L. Coraci, G. Cortellessa, and A. Orlandini, “Adaptive reminders in an ambient assisted living environment,” in *Ambient Assisted Living: Italian Forum 2014*, B. Andò, P. Siciliano, V. Marletta, and A. Monterù, Eds., Berlin, DEU: Springer International Publishing AG, 2015, pp. 219–230.
- [20] R. De Benedictis, A. Umbrico, F. Fracasso, G. Cortellessa, A. Orlandini, and A. Cesta, “A two-layered approach to adaptive dialogues for robotic assistance,” in *2020 29th IEEE*

- International Conference on Robot and Human Interactive Communication (RO-MAN)*, 2020, pp. 82–89.
- [21] A. Umbrico, G. Cortellessa, A. Orlandini, and A. Cesta, “Modeling affordances and functioning for personalized robotic assistance,” in *Principles of Knowledge Representation and Reasoning: Proceedings of the Sixteenth International Conference*, Palo Alto, California: The AAAI Press, 2020.
- [22] D. Kahneman, “A perspective on judgment and choice: Mapping bounded rationality,” *Am. Psychol.*, vol. 58, no. 9, pp. 697–720, 2003.
- [23] B. Ganesan, T. Gowda, A. Al-Jumaily, K. N. K. Fong, S. K. Meena, and R. K. Y. Tong, “Ambient assisted living technologies for older adults with cognitive and physical impairments: A review,” *Eur. Rev. Med. Pharmacol. Sci.*, vol. 23, no. 23, pp. 10470–10481, 2019.
- [24] A. Queirós and N. P. Rocha, “Ambient assisted living: Systematic review,” in *Usability, Accessibility and Ambient Assisted Living. Human-Computer Interaction Series*, A. Queirós and N. Rocha, Eds., Cham: Springer, 2018, pp. 13–47.
- [25] M. J. Mataric and B. Scassellati, “Socially assistive robotics,” in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds., Berlin Heidelberg: Springer-Verlag, 2016, pp. 1973–1994.
- [26] A. Di Nuovo, F. Broz, T. Belpaeme, A. Cangelosi, F. Cavallo, R. Esposito, et al., “Toward usable and acceptable robot interfaces for the elderly: The robot-era project experience,” *Int. Psychoger.*, vol. 27, p. 179, 2015.
- [27] S. Cosar, M. Fernandez-Carmona, R. Agrigoroaie, J. Pages, F. Ferland, F. Zhao, et al., “Enrichme: Perception and interaction of an assistive robot for the elderly at home,” *Int. J. Soc. Robot.*, vol. 12, pp. 779–805, 2020.
- [28] M. Merten, A. Bley, C. Schroeter, and H. Gross, “A mobile robot platform for socially assistive home-care applications,” in *Proceedings of the 7th German Conference on Robotics, ROBOTIK 2012*, 2012.
- [29] M. Nani, P. Caleb-Solly, S. Dogramadgi, C. Fear, and H. Heuvel, “Mobiserv: An integrated intelligent home environment for the provision of health, nutrition and mobility services to the elderly,” in *Proceedings of the 4th Companion Robotics Workshop*, 2010.
- [30] H. Van den Heuvel, C. Huijnen, P. Caleb-Solly, H. H. Nap, M. Nani, and E. Lucet, “Mobiserv: A service robot and intelligent home environment for the provision of health, nutrition and safety services to older adults,” *J. Gerontechnol.*, vol. 11, no. 2, p. 373, 2012.
- [31] G. S. Martins, L. O. Santos, and J. Dias, “The GrowMeUp project and the applicability of action recognition techniques,” in *Proceedings of the Third Workshop on Recognition and Action for Scene Understanding (REACTS)*, 2015.
- [32] I. Kostavelis, D. Giakoumis, S. Malasiotis, and D. Tzovaras, “Ramcip: Towards a robotic assistant to support elderly with mild cognitive impairments at home,” in *Pervasive Computing Paradigms for Mental Health*, S. Serino, A. Matic, D. Giakoumis, G. Lopez, and P. Cipresso, Eds., Cham: Springer International Publishing, 2016, pp. 186–195.
- [33] DALI. Dali project. [Online; last visit on 25-03-2020].
- [34] ACANTO. Acanto project. [Online; last visit on 25-03-2020].
- [35] F. Ferrari, S. Divan, C. Guerrero, F. Zenatti, R. Guidolin, L. Palopoli, et al., “Human-Robot interaction analysis for a smart walker for elderly: The ACANTO interactive guidance system,” *Int. J. Soc. Robot.*, vol. 12, no. 2, pp. 479–492, 2019.
- [36] R. Pérez-Rodríguez, P. A. Moreno-Sánchez, M. Valdés-Aragonés, M. Oviedo-Briones, S. Divan, N. García-Grossocordó, et al., “FriWalk robotic walker: usability, acceptance and UX evaluation after a pilot study in a real environment,” *Disabil. Rehabil. Assist. Technol.*, vol. 15, no. 6, pp. 718–727, 2020.
- [37] T. Fong, I. Nourbakhsh, and K. Dautenhahn, “A survey of socially interactive robots,” *Robot. Auton. Syst.*, vol. 42, no. 3–4, pp. 143–166, 2003.
- [38] E. Ferrari, B. Robins, and K. Dautenhahn, “Therapeutic and educational objectives in robot assisted play for children with autism,” in *RO-MAN 2009-The 18th IEEE International Symposium on Robot and Human Interactive Communication*, 2009, pp. 108–114.
- [39] D. Feil-Seifer and M. J. Mataric, “Defining socially assistive robotics,” in *IEEE 9th International Conference on Rehabilitation Robotics*, 2005.
- [40] A. Tapus and M. J. Mataric, “Emulating empathy in socially assistive robotics,” in *AAAI Spring Symposium: Multidisciplinary Collaboration for Socially Assistive Robotics*, 2007, pp. 93–96.
- [41] C. R. Rogers, “Empathic: An unappreciated way of being,” *Counseling Psychol.*, vol. 5, no. 2, pp. 2–10, 1975.
- [42] A. Valenti, A. Block, M. Chita-Tegmark, M. Gold, and M. Scheutz, “Emotion expression in a socially assistive robot for persons with parkinson’s disease,” in *Proceedings of the 13th ACM International Conference on Pervasive Technologies Related to Assistive Environments, PETRA ’20*, Association for Computing Machinery, 2020, art. 7.
- [43] B. De Carolis, S. Ferilli, and G. Palestra, “Simulating empathic behaviour in a social assistive robot,” *Multimed. Tools Appl.*, vol. 76, pp. 5073–5094, 2017.
- [44] D. Casey, H. Felzmann, G. Pegman, C. Kouroupetoglou, K. Murphy, A. Koumpis, et al., “What people with dementia want: Designing MARIO an acceptable robot companion,” in *Computers Helping People with Special Needs*, K. Miesenberger, C. Bühler, and P. Penaz, Eds., Cham: Springer International Publishing, 2016, pp. 318–325.
- [45] HOBbit. Hobbit project. [Online; last visit on 25-03-2020].
- [46] D. Fischinger, P. Einramhof, K. Papoutsakis, W. Wohlkinger, P. Mayer, P. Panek, et al., “Hobbit, a care robot supporting independent living at home: First prototype and lessons learned,” *Robot. Auton. Syst.*, vol. 75, pp. 60–78, 2016.
- [47] J. Pripfl, T. Körtner, D. Batko-Klein, D. Hebesberger, M. Weninger, C. Gisinger, et al., “Results of a real-world trial with a mobile social service robot for older adults,” in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2016, pp. 497–498.
- [48] I. Papadopoulos, “The Papadopoulos, Tilki and Taylor model of developing cultural competence,” *Transcultural Health and Social Care: Development of Culturally Competent Practitioners*, I. Papadopoulos, Ed., Edinburgh: Churchill Livingstone Elsevier, 2006.
- [49] C. Papadopoulos, T. Hill, L. Battistuzzi, N. Castro, A. Nigath, G. Randhawa, et al., “The caresses study protocol: testing and evaluating culturally competent socially assistive robots among older adults residing in long term care homes through

- a controlled experimental trial,” *Arch. Public Health*, vol. 78, art. 26, 2020.
- [50] B. Bruno, C. T. Recchiuto, I. Papadopoulos, A. Saffiotti, C. Koulouglioti, R. Menicatti, et al., “Knowledge representation for culturally competent personal robots: Requirements, design principles, implementation, and assessment,” *Int. J. Soc. Robot.*, vol. 11, no. 3, pp. 515–538, 2019.
- [51] M. Jung and P. Hinds, “Robots in the wild: A time for more robust theories of human-robot interaction,” *ACM Trans. Human-Robot Interact. (THRI)*, vol. 7, no. 1, art. 2, 2018.
- [52] B. R. Duffy and G. Joue, “Intelligent robots: The question of embodiment,” in *Proceedings of BRAIN-MACHINE’2000*, 20–22, 2000.
- [53] B. Miller and D. Feil-Seifer, “Embodiment, situatedness, and morphology for humanoid robots interacting with people,” in *Humanoid Robotics: A Reference*, A. Goswami and P. Vadakkepat, Eds., Dordrecht, Netherlands: Springer, 2016, pp. 1–23.
- [54] E. Davis, G. Marcus, and N. Frazier-Logue, “Commonsense reasoning about containers using radically incomplete information,” *Artif. Intell.*, vol. 248, pp. 46–84, 2017.
- [55] J. E. Laird, C. Lebiere, and P. S. Rosenbloom, “A standard model of the mind: Toward a common computational framework across artificial intelligence, cognitive science, neuroscience, and robotics,” *AI Magazine*, vol. 38, no. 4, pp. 13–26, 2017.
- [56] P. Langley, J. E. Laird, and S. Rogers, “Cognitive architectures: Research issues and challenges,” *Cognit. Syst. Res.*, vol. 10, no. 2, pp. 141–160, 2009.
- [57] A. Lieto, M. Bhatt, A. Oltramari, and D. Vernon, “The role of cognitive architectures in general artificial intelligence,” *Cognit. Syst. Res.*, vol. 48, pp. 1–3, 2018.
- [58] A. Umbrico, G. Cortellessa, A. Orlandini, and A. Cesta, “Toward intelligent continuous assistance,” *J. Ambient Intell. Human. Comput.*, vol. 12, no. 4, pp. 4513–4527, 2021.
- [59] F. Ingrand and M. Ghallab, “Deliberation for autonomous robots: A survey,” *Artif. Intell.*, vol. 247, pp. 10–44, 2017.
- [60] K. Rajan and A. Saffiotti, “Towards a science of integrated AI and Robotics,” *Artif. Intell.*, vol. 247, pp. 1–9, 2017.
- [61] H. Deeken, T. Wiemann, and J. Hertzberg, “Grounding semantic maps in spatial databases,” *Robot. Autonom. Syst.*, vol. 105, pp. 146–165, 2018.
- [62] R. Porzel, M. Pomarlan, D. Beßler, R. Malaka, M. Beetz, and J. Bateman, “A formal model of affordances for flexible robotic task execution,” in *ECAI 2020 – 24th European Conference on Artificial Intelligence*, 2020.
- [63] M. Tenorth and M. Beetz, “Knowrob – knowledge processing for autonomous personal robots,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009*, Oct 2009, pp. 4261–4266.
- [64] A. Umbrico, A. Cesta, G. Cortellessa, and A. Orlandini, “A goal triggering mechanism for continuous human-robot interaction,” in *AI\*IA 2018-Advances in Artificial Intelligence*, C. Ghidini, B. Magnini, A. Passerini, and P. Traverso, Eds., Cham: Springer, 2018, pp. 460–473.
- [65] A. Umbrico, A. Cesta, G. Cortellessa, and A. Orlandini, “A holistic approach to behaviour adaptation for socially assistive robots,” *Int. J. Soc. Robot.*, vol. 12, no. 3, pp. 617–637, 2020.
- [66] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*, second edition, Cambridge, MA, United States: The MIT Press, 2018.
- [67] J. Boger, P. Jackson, M. Mulvenna, J. Sixsmith, A. Sixsmith, A. Mihailidis, et al., “Principles for fostering the transdisciplinary development of assistive technologies,” *Disabil. Rehabil. Assist. Technol.*, vol. 12, no. 5, pp. 480–490, 2017.
- [68] S. Rossi, F. Ferland, and A. Tapus, “User profiling and behavioural adaptation for HRI: A survey,” *Pattern Recognit. Lett.*, vol. 99, pp. 3–12, 2017.
- [69] I. Awaad, G. K. Kraetzschmar, and J. Hertzberg, “The role of functional affordances in socializing robots,” *Int. J. Soc. Robot.*, vol. 7, no. 4, pp. 421–438, 2015.
- [70] B. Bruno, C. T. Recchiuto, I. Papadopoulos, A. Saffiotti, C. Koulouglioti, R. Menicatti, et al., “Knowledge representation for culturally competent personal robots: Requirements, design principles, implementation, and assessment,” *Int. J. Soc. Robot.*, vol. 11, no. 3, pp. 515–538, 2019.
- [71] G. Buisan, G. Sarthou, and R. Alami, “Human aware task planning using verbal communication feasibility and costs,” in *Social Robotics*, A. R. Wagner, D. Feil-Seifer, K. S. Haring, S. Rossi, T. Williams, H. He, et al., Eds., Cham: Springer International Publishing, 2020, pp. 554–565.
- [72] S. Devin and R. Alami, “An implemented theory of mind to improve human-robot shared plans execution,” in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2016, pp. 319–326.
- [73] S. Lemaignan, M. Warnier, E. Akin Sisbot, A. Clodic, and R. Alami, “Artificial cognition for social human-robot interaction: An implementation,” *Artif. Intell.*, vol. 247, pp. 45–69, 2017.
- [74] A. Sharkey and N. Sharkey, “Granny and the robots: ethical issues in robot care for the elderly,” *Ethics Inform. Technol.*, vol. 14, no. 1, pp. 27–40, 2012.
- [75] T. Vandemeulebroucke, B. D. de Casterlé, and C. Gastmans, “The use of care robots in aged care: A systematic review of argument-based ethics literature,” *Arch. Gerontol. Geriatr.*, vol. 74, pp. 15–25, 2018.
- [76] M. M. A. de Graaf, S. B. Allouch, and J. A. G. M. van Dijk, “Long-term acceptance of social robots in domestic environments: Insights from a user’s perspective,” in *The 2016 AAAI Spring Symposium Series*, March 2016, pp. 96–103.