Deploying Robots in Ambient Assisted Living Environments: Potential Benefits, Challenges, and Future Research Directions

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Abstract* - The increase of life expectancy and the growing senior population lead to an important development of smart equipment for healthcare and assistive services to support elderly people, especially when living at home. Elderly people living alone with degenerating physical and cognitive abilities need innovative assistance techniques. Such techniques or Internet-Of-Things (IOT) systems can be classified as wearables, smart infrastructures, and mobile IOT. All these systems aim to help people in their daily activities, especially when they are dependent and/or have mobility impairments and/or cognitive impairments. IoT systems collect data and can complete action while connected to the Internet. Moreover, robotic systems can also be deployed at home for the safety and comfort of individuals. Usually, robotics and IOT systems are used separately. In this paper, our aim is to discuss the challenges associated with their combined use at home for elderly and identify future research directions in this area.

Keywords: Ambient Assisted Living, IOT, Robot, privacy.

I. Introduction

The world population aged over 80 years will approximate 202 million by 2030 and is expected to reach 434 million in 2050 [1]. In order to enhance the independence and the autonomy of elderly and dependent people, assistive technologies, such as IOT devices and robots, have been developed. For example, smart homes and Ambient Assisted Living (AAL) benefit from these IOT devices and contribute to the well-being and caring of elderly people. As shown in the review conducted in [2], various IOT systems have been developed and are based on sensors and actuators for assisting degenerating physical and cognitive abilities of individuals. These systems include home automation systems, home activity detectors, wearable sensors and technologies for remote health management [2]. Additionally, robots are becoming increasingly available and experiments have been conducted to use them for helping care workers or elderly in their daily activities. However, these technologies, i.e., AAL and robots, have mostly been considered separately. The contributions of this paper are therefore centered on (1) discussing their limitations when considered separately, (2) identifying the potential benefits and challenges resulting from a combination of both AAL environments and robots, and (3) proposing new research directions to tackle these challenges. To this end, we provide in Section 2 details about AAL and smart homes and comment on their limitations. In Section 3, we discuss the potential benefits of robots for elderly assistance. Section 4 is dedicated to the description of how robots and AAL could be integrated and the benefit of this combination. Since such a combination has not been studied yet, we comment on challenges that need to be addressed and identify future research directions in Section 5 and 6, respectively.

II. Smart homes and AAL

A. Backgrounds and Benefits

Connected devices are becoming essential to ensure comfort and safety for elderly people in smart and connected homes. The need to save energy, time, and improve comfort at home has led to the development of many applications and solutions for elderly and dependent people. These connected systems are used to help them in their daily activities and life. Several research studies have focused on assisting dependent persons who wish to stay at home [3], but also to identify urgent situations, which could be dangerous for the person [4]. To realize these functions, e.g., recognize daily activities, smart homes systems use a set of connected sensors and/or IOT devices deployed in the users' environment or worn by them. This field is constantly evolving because of the growing number of elderly people and the development of the silver economy. According to [5], the number of IOT devices has now been expected to exceed 70. All these devices generate data that allow to, e.g., (1) identify the number of people occupying a home, (2) ensure their energy comfort, (3) activate alerts, and (4) ensure user safety by applying data fusion algorithms. Moreover, such environments can help in reducing risks for people living alone. For example, sensors and/or IOT devices can prevent fall, overdose of prescription pills or undernourishment [6-7].

As people become older, they often become increasingly mentally and/or physically dependent. As a result, equipping their home with such devices allows better assistance. In most cases, such systems connect devices to the Internet or smartphones in order to collect data from various applications, conduct different analyses and provide feedback to the users or to third parties for data analysis [2]. For example, feedback includes alerts or statistics [2]. While some feedback may be considered as intrusive by users, they may also increase users' safety and/or provide transparency about the collected and processed data. Besides, analyzing data can improve decision making related to home security, energy efficiency, etc. So, such equipment can contribute to improving the elderly's quality of life and reducing costs associated with their personal assistance (as compared to nurses). In fact, many IOT systems have been developed for medical purposes, such as hypertension monitoring and detection, high cholesterol monitoring, heart disease monitoring and management, for arthritis, for diabetes, and so on [2].

Among these existing systems, we especially focus on the concepts of activity recognition and anomaly detection that have been studied in several research projects in recent years, including:

- *Dem@Care*[1] *Project (2011-2015)* (Dementia Ambient Care) The project funded by the European Union aims to contribute to the diagnosis, assessment, maintenance and promotion of independence of people with dementia, by deepening the understanding of how the disease affects their daily life and behavior. It implements a closed-loop, multi-parametric remote management solution that provides adaptive feedback to the person with dementia, while including clinicians in the remote monitoring, allowing them to have an overview of the person's health status and progress.

- *SECURE*[2] *(2014-2015)* (Intelligent System for Early Diagnosis and Monitoring at Home): This project was funded by a grant from the Lombardy Region and the Italian Ministry of Education. It has developed an activity recognition system enhanced by a new solution for abnormal activity recognition tailored to elderly at home.

- *E-MONITOR'ÂGE*[3] *(2010-2016)*: This project funded by the *French Inter-ministerial Fund* (FUI) aims to adapt and adjust care, to improve well-being and safety for dependent elderly people in retirement homes.

- *COCAPS*[4] *(2016-2021)*: This project has been financed by FUI and aims to identify user activities for energy efficiency and autonomy by analyzing data provided by low-cost sensors developed within the scope of the project.

- *ADAM*[5] *(2021-2022)* (Analysis of activity data from ambient sensors in shared houses): The project funded by the Occitanie Region aims to implement a system of ambient sensors to observe the activities of elderly people in shared houses. The purpose of data analysis and lifestyle identification is to anticipate risks. Different types of sensors (resistance, capacitance, conduction, heat transfer, temperature, presence, etc.) measure physical properties of the smart environment in order to detect the spatio-temporal states of physical or environmental situations. The data provided by the sensors are first acquired then processed and analyzed in order to make decisions and adjust the environment of people to their activities or behaviors (alerts, alarms, varying the temperature, ventilating, lighting, etc.).

B. Limitations of AAL and smart homes

While smart homes and AAL offer different advantages as detailed in Section II.A, they also suffer from the following limitations.

The first limitation is that elderly often need to carry wearable devices with them at home. These devices include smart watches, dedicated fall detectors, and/or smartphones. In the case of smartwatches and smartphones, the devices run a dedicated application that may be coupled with the surrounding environment. Relying on these devices is often inefficient because elderly people remove them and/or lose them or simply forget to wear them. Besides, they may also forget to recharge them.

Secondly, another difficulty with smart homes and AAL is the human-computer interactions including controlling it using dedicated interfaces [8]. Elderly people are often reluctant to use new technologies especially when these systems are coupled to a smartphone or tablet for turning on the light or changing the thermostat [9]. Elderly who are not used to these technologies have many difficulties to access and remember steps needed to use the interface [9]. It is even more difficult when individuals present declining cognitive and/or physical disabilities. A possible solution for these problems is to rely on voice interfaces, so that elderly do not need to physically interact with graphical user interfaces and remember the associated steps.

[1] https://demcare.eu/
[2] http://secure.ewlab.di.unimi.it/
[3] https://www.univ-orleans.fr/fr/pole-capteurs/presentation/projets
[4] https://www.univ-orleans.fr/fr/pole-capteurs/presentation/projets
[5] http://mi.iut-blagnac.fr/?page_id=1104&lang=fr

They still need to remember the correct voice commands to reach their goals, though. To this end, smart voice assistants emerged in 2011 [10]. These assistants can also help elderly to be reminded to take medications, to contact medical professionals and emergency services, etc.

Many individuals are also reluctant to use IOT devices because of the security and privacy issues [10]. In addition to the threats to privacy that may result from the utilization of these systems [11] [12], users may need to interact with them to better protect their security (and privacy) through the different steps of the device(s) lifecycle [13]. For example, this includes setting up and managing authentication and authorization functions. While these functions are highly relevant for any IoT systems [14], their configuration and maintenance complicate the access for elderly people and do not encourage them to use smart technologies. Besides, if these applications are not secured, anyone could access sensitive information and violate their privacy.

III. Robots as Assistant

The deployment of robots for elderly assistance has been studied in the last years (e.g., in [15-18]). Existing studies show that elderly people benefit from interactions with these robots due to their offered advantages. Indeed, robots can remind elderly people to conduct activities or tasks during the day [19]. Such reminders help them in organizing their daily activities, thus structuring their daily life and allowing them to live longer independently and at home [20]. Additionally, telepresence robots can support more frequent interactions with family and friends by enabling their communication. As a result, the robots' presence can prevent loneliness and increase their social feelings [21-22]. Depending on the type of robots, they can also assist elderly people in walking [23] or help them in finding and navigating to certain locations [24], thus reducing their dependency on others.

As shown in these studies, different robots can be deployed depending on the required functionalities. In turn, these different functionalities are based on different sensors and actuators. For example, a robot needs a microphone and a speaker to communicate with its users. Similarly, it needs at least one camera to create an image from its environment. Table 1 illustrates the diversity of existing robots with a selection of their interaction possibilities based on the embedded sensors. Note that the selected robots are publicly available and often used in scientific research on human-robot interactions.

While these robots propose different functionalities based on their embedded sensors, they may however not offer all sensors and functions to fully assist elderly people. For example, Double 3 does not have a depth sensor and hence cannot create a 3D map of the environment. Additionally, the embedded sensors may not have a sufficient resolution by default for some applications or due to user interactions. For example, the ultrasonic sensors from NAO are placed on its chest, where the robot is normally grabbed. Therefore, users' hands may cover them and hence prevent their function. Moreover, some robots, such as social robots, can only process information about users in their vicinity. This means that users outside the robots' camera or microphone ranges cannot be assisted with the same reliability. For example, if an elderly person would fall in another room, the robot may not detect it. Another issue is that most embedded sensors are placed on one side of the robots to gather information about objects and users located in front of them. Therefore, most robots are not able to capture and react to something happening behind them. Consequently, robots may not only fail in reacting to user interactions, but also misinterpret an observed situation or even miss important information about their environment due to the lack of relevant sensors. For example, none of the social robots in Table 1 have a temperature camera or sensor. They are hence unable to detect and determine if a certain location or place (e.g. kitchen plate) is safe for interaction.

In summary, existing robots offer interesting capabilities to assist elderly people in their environment. However, they still show limitations when deployed in isolation due to a limited set of available sensors by default, their position on the robot, and their failure in capturing events beyond their range.

TABLE I. Examples of robots with some of their functionalities.

Functionalities/ Robots	*Pepper*[6]	*CruzR*[7]	*Double 3*[8]	*Nao*[9]
Verbal communication	x	x	x	x
2D image creation	x	x	x	x
3D image creation	x	x		
Moving (Driving/walking)	x	x	x	x

[6] https://www.aldebaran.com/de/pepper
[7] https://zorabots.be/robtos/cruzr
[8] https://www.doublerobotics.com/double3.html
[9] https://www.aldebaran.com/de/nao

IV. Benefits of the Inclusion of Robots in AAL Environments

In this paper, we argue that the deployment of robots in AAL environments, such as described in Sec. II, can address the individual limitations of both systems. Indeed, robots are limited by the data recorded by the sensors embedded by default. In contrast, an AAL system usually includes only static sensors. By sharing information and interacting together, their combination can contribute in solving the aforementioned issues. The combination of both technologies has however only been explored in a very limited number of studies until now. In these studies, the collaboration of both systems and the resulting benefits have been considered.

For example, a mobile robot supports an AAL system in [25]. In this scenario, the robot moves and uses its camera to locate people in a room, where the AAL has no information, thus covering potential black spots resulting from the static cameras of the AAL system. As a result, the elderly people can be localized in their environment. The information can then be used to react if they fall and need help.

Another example is presented in [26], where an AAL system in form of a biometric bracelet and an “interaction pyramid” works together with a telepresence robot. A user can interact with the interaction pyramid to obtain general information about, e.g., the weather, or more personalized information like appointments or medication plans. In other words, the interaction pyramid provides similar functionalities to a usual smart speaker. During a medical appointment via the telepresence robot, the biometric bracelet can send health information to the doctor. Besides, the doctor can call for an appointment with the user via the telepresence robot based on the health information collected by the biometric bracelet.

A combination of an AAL system with a mobile robot is further described in [27]. In this scenario, the AAL system locates and analyzes the users’ activities based on sound. If users need help, the robot can be navigated by the AAL system, but the robot is not in direct contact with the users and does not recognize them.

Moreover, a static robot is connected to an AAL system in [28]. The AAL system includes different sensors (e.g. Kinect camera). The AAL system can process the data from its own sensor and from the robot in order to have more information about the environment and to detect both humans and objects. Through this combination, the enhanced human and object detection helps the robot in better interacting with the users, as its gaze can be better oriented.

As a result, these existing works confirm that a combination of both AAL systems and robots can lead to improved functionalities. In these scenarios, the AAL systems are enhanced by the robots that cater for physical interactions. In contrast, the robots benefit from the information gathered by the AAL systems. Furthermore, the AAL systems benefit from the mobile sensors embedded in the robots, while the robots benefit from the sensors distributed in the rooms and contributing to the AAL systems.

While these few studies showcase the benefits of such a combination, we argue that the field is still in its infancy and unprecedented applications and functionalities could be developed when combining these two distinct worlds that have mainly been considered in isolation until now (at the exception of our detailed examples). Further exploring such cooperation is not only interesting from a research perspective, but will also benefit elderly people and support them in their daily life in the long run.

V. Selected Challenges and Future Research Directions

The inclusion of robots in an AAL environment is expected to raise different challenges about communication, data management and fusion, and privacy. We discuss these three challenges and associated future directions in the following sections.

A. *Communication, Data Management and fusion*

Including robots in an AAL environment requires managing the communication and coordinating data collection within an interoperable network. In the literature review, we have only found a few studies that integrate the robots’ sensors with the sensor deployed in the environments and vice versa.

For example, a recent study [29] uses sensors to allow the robot to interact with humans for ensuring safety functions. In this case, the communication between the robot and the deployed sensors (capacitive and inductive sensors) where sensors could detect the human body and the metal sensitively and distinguish whether an object is a human body. However, the following issues have not been addressed.

In [30], the authors aim to identify how robots and sensors could help care workers for elderly patients at home or at nursing homes. Nevertheless, the authors do not indicate how data are collected and managed.

The most relevant publication within those included in our literature review that discusses the management of communication between robots and sensors is [30]. The author points out different problems that still need to be solved, such as the efficient use of the communication channel, the algorithm to use for data fusion, the uncertainty concerning information transmitted, the sensor robustness and the complex management of software.

Another challenge is the sensor placement according to the robot position and type. In fact, data are collected from sensors and processed using fusion algorithms in order to help care workers to make decisions about individual conditions. As a result, the sensor placement has to consider the robot size and movement to interact with it and to collect significant and relevant data.

To monitor the real-time user state, smart medical services are currently involved. In the future, this means that robots could be introduced in elderly's smart homes. In this case, multiple data from sensors and robots are collected for data processing and fusion. A multi sensor fusion method based on an interpretable neural network has been designed and analyzed to improve the performance of fusion decision making in [31]. However, we have not found additional references in our literature research that tackle this field. Consequently, combining sensors and robots means collecting multimodal data for processing and fusion. The challenge will be to develop algorithms in order to identify the location and current state of the elderly. As a basis for this development, we could leverage existing algorithms and methods originally developed for robots already deployed in the industry and manufacturing sector that communicate with their environment. In fact, to the best of our knowledge, no research deals with the fusion of sensor data and robot data in the case of healthcare systems. This research gap however may postpone the deployment of such systems combining both technologies, i.e., sensors and robots in elderly's home.

B. *Privacy*

In none of existing solutions proposed in [26-28] and described in section IV, security and privacy aspects have been mentioned and/or implemented. This lack of consideration is likely to negatively impact the acceptance of users to the whole system. Indeed, during user studies with robots only, participants have expressed concerns about privacy issues related to their deployment [15]. For example, elderly's main concern was the robot's camera, and they indicated to feel observed In [15]. Such concerns do not only impact the acceptance of the robots by elderly, but also lead to privacy-protecting behaviors. Elderly have censored their conversation or moved to another room when in the presence of robots. In most severe cases, the elderly's privacy concerns have led to the robot abandonment.

We hence strongly believe that such concerns must be addressed when designing joint systems between AAL environments and robots. Indeed, their combination will especially endanger the elderly's informational privacy due to the presence of sensors deployed in their environment and embedded in the robot. In addition to fostering users' acceptance, the design, implementation, and integration of dedicated privacy-preserving solutions are mandatory to be compliant with current data protection regulations, such as the European General Data Protection Regulation (GDPR). Different works including [32-44] have proposed guidelines and recommendations for the design of privacy-preserving robots. However, they do not include any practical solutions or implementations. Moreover, they solely focus on robots and not their combination with external sensors and actuators deployed in the environment like we do. Nevertheless, there exist different privacy-preserving solutions dedicated to robots. For example, they include light signals to inform users about data collection [45–47], more privacy-friendly sensors [48, 49], leveraging blockchain as basis for transparency [50], as well as identifying [51-53] and hiding [54-62] sensitive information. Again, these solutions are designed for robots only. Therefore, new solutions should be developed to be deployed in AAL environments in the presence of robots. For example, such solutions could include the design of sensor-based functions that respect the principle of data minimization, i.e., collect only the data necessary for the realization of the underlying functions. As a result, this may mean that the data collected by the robots and the sensors deployed in the environment should be jointly optimized to simultaneously fulfill the requirements in terms of privacy protection and data utility. Moreover, the collected, processed, and exchanged data between the robots and the sensors should be protected against usual threats to security by means of adapted security mechanisms as highlighted in [63]. Due to the heterogeneity and limited resources of the robots as well as the IOT devices and their sensors, ensuring security may be challenging. Other solutions to be developed include transparency solutions tailored to elderly that are easy to understand and use for them. By using them, elderly will be able to see and understand, e.g., which data are collected about and for which purposes. As highlighted in [35-64], transparency has not been sufficiently addressed in presence of robots only and thus in our considered scenario too. We therefore argue that proposing transparency solutions is however important because it has been shown that it is difficult for elderly to understand aspects related to the collection, processing, storage, and sharing of information about them [65,66]. Such understanding is however necessary to be able to give an informed consent [33, 34, 67] about the utilization of both robots and AAL environments. Without informed consent, elderly are not fully able to exercise their right to rights to self-determination [68]. Besides, transparent processing is requested by the GDPR (Art. 5(1)(a)). To the best of our knowledge, no usable transparency solution exists tailored to elderly's needs and capabilities in terms of cognitive ability, motor control, and perceptual functions. We therefore strongly encourage the development of such solutions that should be designed with and for elderly, thus involving them during the whole design, testing, and evaluation process. As a basis for this development, lessons learned from other domains and user groups, such as [69-71], could be considered, but should be adapted to the usable available interfaces, collected data types, and targeted users, i.e., elderly. Based on these transparency solutions, elderly could also control the collected data according to their own preferences to further foster their acceptance of the system.

While the GDPR focuses on informational privacy, i.e., to control collected and processed information, the introduction of robots in AAL systems introduce additional dimensions of privacy that must be taken into consideration, but have not attracted much attention yet. For example, according to [72-75], physical privacy and social privacy can also be endangered in the presence of robots. To guarantee the former, we must ensure that the users' physical accessibility and personal space are not infringed. In other words, the robot should not touch the users, navigate too close to them, or visit them in rooms and situations considered as sensitive, if they do not wish so. For example, the results of our study [76] shows that both bathroom and bedroom are locations in which elderly people would especially dislike to be accompanied by a robot. For the latter, the social interactions with the robots should respect the users' "right to be let alone" as defined by Warren and Brandeis. This means in our context that the robot should stop interacting with the users when desired.

VI. Conclusions

In this paper, we have discussed the limitations of IoT systems and robots when deployed separately to assist elderly living alone at home. We have further proposed to combine both technologies to address these limitations. Such a combination however requires additional efforts to address the challenges we have further highlighted in this paper. Since robots are already used in the manufacturing sector, we suggest that the solutions to be developed for the healthcare systems could be inspired from existing solutions deployed in this area. Addressing these challenges is however important, so that elderly can safely benefit from these technologies and remain in their living environment with their privacy respected.

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