robotics

Review

A Review on the Use of Mobile Service Robots in Elderly Care

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Abstract: Global demographics trend toward an aging population. Hence, there will be an increased social demand for elderly care. Recently, assistive technologies such as service robots have emerged and can help older adults to live independently. This paper reports a review starting from 1999 of the existing mobile service robots used for older adults to grow old at home. We describe each robot from the viewpoint of applications, platforms, and empirical studies. Studies reported that mobile social robots could assist older adults throughout their daily activities such as reminding, household tasks, safety, or health monitoring. Moreover, some of the reported studies indicate that mobile service robots can enhance the well-being of older adults and decrease the workload for their caregivers.

Keywords: mobile service robot; ageing in place; older adults care; social assistive robot

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1. Introduction

Nowadays, most people worldwide can expect to live into their sixties and beyond due to novel technologies, medical advancements and social developments. Therefore, almost all countries are experiencing growth in the proportion of their older adults (OAs, aged 65 years or more) in their population.

Worldwide, the number of OAs is predicted to increase dramatically from 702 million in 2019 to 1.5 billion in 2050, which will be 16% of the population [1]. Some studies [2] report that the population of OAs in Europe will rise from 90.5 million in 2019 to 129.8 million by 2050 (approximately 29% of the population). Similarly, about 22% of the U.S. [3] and 25% of the Canada's [4] population will be over age 65 in 2050.

Normal ageing is associated with a decline in cognitive, physical and perceptual capabilities. This factor influences the ability of an OA to perform daily activities and hence causes societal and economic pressure on both governments and families [1,5]. However, the related challenges about OA's independent ageing are tackled due to progress reported in artificial intelligence (AI) and robotics [6–8].

Recently, socially assistive robots (SARs) have been considered as one possible care option to promote OAs' well-being and assist families by diminishing their burden of care [9]. In addition, the COVID-19 pandemic accelerated the use of personal assistant robots to provide safer services [10,11]. The global market of SARs is predicted to grow from USD 321 million in 2018 to USD 836 million by 2025 [12]. Some countries have made a high amount of investment in care robots. For instance, the Japanese government invested USD 45 million in SARs to support the shortage of caregivers [13], and the EU health sector considers SARs an outstanding option for future expense saving in healthcare [14]. To this end, several research papers focused on developing SARs for OAs to reduce loneliness [15], especially during the COVID-19 spread [16], help in household tasks [17], detect risk [18], feed [19], remind a user of tasks or to take their medicine [20], enhance cognitive function [21], set [22] or clean the table [23] and monitor a user's state of health [24].

Moreover, a variety of studies have demonstrated promising results of interactions between OAs and SARs. As a few examples, Amudhu [25] presented a short overview of SARs' impact on OAs' life, confirming that SARs would be the preference for companions of OAs in the future. Kachouie et al. [26] concluded that care robots could promote OAs' quality of life and alleviate caregivers' workload. Correspondingly, in [27], it was found that the eldercare robots were helpful, friendly and acceptable. Salatino et al. [28] performed a practical investigation to assess the interest of caregivers and OAs toward service robots. In [28], participants believed that robots would make life easier and that they needed SARs to decrease loneliness, monitor health conditions and improve mood.

Pino et al. [29] evaluated the acceptance rate of SARs among 25 participants, including healthy OAs, elderly with mild cognitive impairment (MCI) and informal caregivers. Results showed that most participants preferred a human-like robot and cognitive support functionality. While caregivers were interested in using SAR during the experience, other participants were ready to use it in future. A study with older participants from Italy and Germany was presented in [13] to investigate the cultural acceptance rate, preferred functionalities and marketability of SARs. This study was conducted by filling in a questionnaire after watching a video of some SARs. The results showed a strong relationship between technology acceptance and individual readiness to invest money. Moreover, cleaning, lifting heavy things and grabbing objects were more appreciated functionalities by respondents. Similarly, the acceptance of assistive robots in the OA community through human–robot interaction (HRI) [30–32] or questionnaire [33–35] was investigated in some studies. Moreover, a detailed review of OAs' experiences with SARs was reported by Vandemeulebroucke et al. in [36].

The objective of proposing SARs to OAs is to offer an intelligent configuration for supporting the primary tasks of independent living [25,30,37]. The SARs can be divided into service robots and companion robots [26]. A significant application of service robots is daily life assistance such as eating, health monitoring, reminding and safety [38,39]. Mobile service robots have a high potential to support daily routines due to a wide variety of capabilities, such as delivering objects, human or object detection, cognition training, entertainment, etc. [40–42].

This review paper highlights research directions on mobile service robots used in aged care since 1999. In other words, it reports the projects focused on mobile service robots with field studies' results to provide valuable information, lessons learned, and future research directions for both research and industrial communities. Our contribution consists in answering the following research questions:

- Are mobile service robots integrated and used in the care of OAs?
- Can mobile service robots help OAs with their daily life requirements at home or in care facilities? Are their capabilities suitable enough?
- What are the challenges and opportunities of using mobile service robots for OAs care?

By answering these questions, we identify the experiences and challenges of OAs interacting with mobile service robots. We also aim to determine whether mobile service robots can improve the well-being of OAs and alleviate the burden of workload for caregivers. Therefore, the potential directions for future research and technology of mobile service robots are determined.

The paper is organized as follows: Section 2 explains the methodology used to select publications for this review paper. Section 3 describes various mobile service robots from the viewpoint of applications and field studies. Moreover, in summary, this section outlines the technology behind the reported mobile service robots. Section 4 discusses open challenges and recommendations for mobile service robots in OAs' care, while Section 5 concludes
the paper.

2. Methodology

The methodology of this paper is based on three main stages: (i) an initial search in digital libraries, (ii) a first screening based on the subject of mobile service robots and (iii) a second filtering based on inclusion criteria. In the first step, the publications of SARs related to OAs care were searched in IEEE Xplore, Scopus, PubMed and Google Scholar. Since these databases consist of a collection of journal or conference papers, the searching process was more comprehensive. All searches were performed through English language publications from 1999 to 2022, with the keywords reported in Table 1. It should be explained that the target robots are mobile ones used to provide a service to older adults. However, for a broader search area, similar keywords such as personal care robot, socially assistive robot and eldercare robot were considered too. Also, asterisks (*) in the table replace multiple characters anywhere in a word.

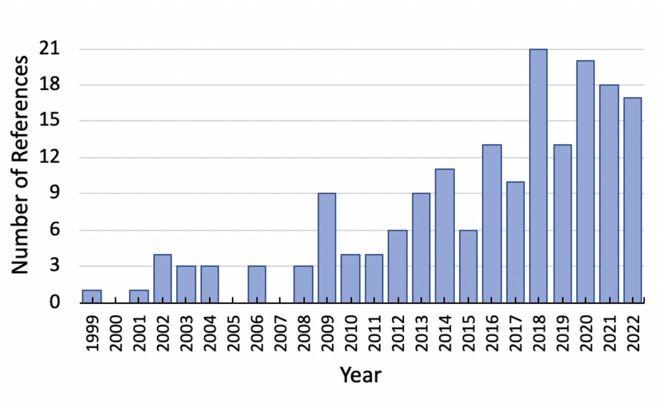
Table 1. Search strategy details.

Database	Search Target	Search Terms
Scopus	"personal care robot", "mobile service robot", "socially assistive robot", "eldercare robot", "assistive robotics "	(TITLE-ABS-KEY (*personal AND care AND robot) OR TITLE-ABS-KEY (*service AND robot) OR TITLE-ABS-KEY (*socially AND assistive AND robot) AND TITLE-ABS-KEY (*eldercare AND robot) AND TITLE-ABS-KEY (*cognitive AND assistance) AND TITLE-ABS-KEY (*assistive AND robotics) AND TITLE-ABS-KEY (*social AND robots)
IEEE Xplore		(("personal care robot" OR "service robot" OR "socially assistive robot" OR "social robots") AND ("eldercare robot" OR "cognitive assistance" OR "assistive robotics"))
PubMed		(personal care robot) AND (service robot) AND (socially assistive robot) AND (eldercare robot) AND (cognitive assistance) AND (assistive robotics) AND (social robots)

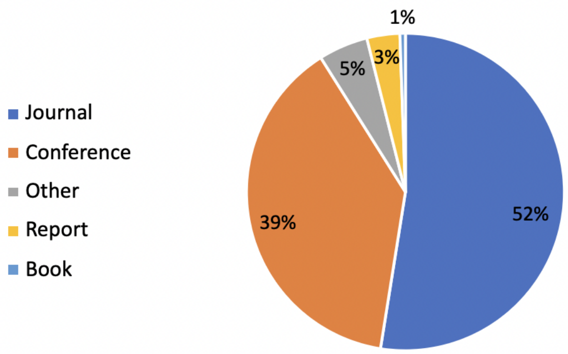
All collected materials relevant to mobile service robots were extracted and categorized in the second stage.

Therefore, in this step, the healthcare, companion or telepresence robots were eliminated. In the final phase, the candidate publications were screened again to select high-quality papers focusing on the practical investigation of mobile service robots. Then, the gathered data were summarized and organized in a meaningful way.

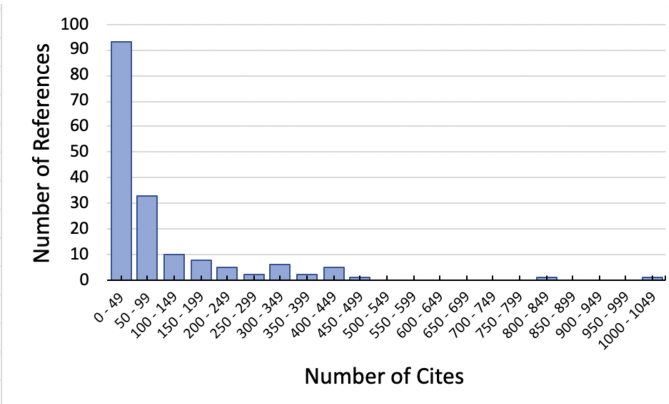
Figure 1 reports the statistics of the selected literature in terms of the number of publications, type of publications and citation scores. Figure 1a shows the number of references per year and, in fact, illustrates a distribution of publications from 1999 to 2022. Figure 1b represents the type of references used in this review paper. The types of publications were "journal", "conference", "report" or "book", and "other" referred to websites or arXiv papers. Moreover, Figure 1c illustrates the number of citations for selected references to provide a comprehensive vision of the quality of the papers. For example, the number of citations for 93 papers was less than 50. For visual simplicity, it should be declared that there was a paper with 3532 citations between the selected references, which is not considered in this figure.



(**a**)



(**b**)



(**c**)

Figure 1. Statistics of the selected literature: (**a**) number of publications per year, (**b**) percentage of various types of publications, and (**c**) number of citations.

3. Mobile Service Robots

This section reviews the technologies behind research projects reported in the literature, focusing on mobile service robots. Each mobile service robot is summarily described as follows: its capabilities, the platform and the applications and practical studies in which it was involved. Moreover, the robots follow a chronological order of publication to give a sense of the field's evolution.

It should be noted that Bardaro et al. [43] reviewed the historical and current landscape of the field of service robots in elderly care. While that work appears to intersect with our work, the perspective on robots' analysis and the objective of the papers are different.

In [43], a novel co-design toolkit based on an ecological framework for service robot interventions was proposed.

3.1. Care-O-Bot

Care-O-bot is a versatile service robot that can aid people in their activities of daily living (ADL). This robot with four generations is the product of constant evolution from 1998 until 2015 by the Fraunhofer Institute for Manufacturing Engineering and Automation (see Figure 2). The main difference between Care-O-bot 4 and previous ones is its modular approach that enables an affordable and customized model [44].

Figure 2. Care-O-bot robots: (1)—1999, (2)—2004, (3)—2009 and (4)—2015 [44].

The Care-O-bot is capable of taking diverse roles in multiple scenarios. This robot can serve as a research platform and in numerous duties, including collection and delivery service, independent living of OAs, security or surveillance tool, greeting and assistance in retail stores or museums [45,46]. Predictably, this robot is equipped with a variety of sensors and modules to navigate autonomously and safely in the environment, communicate with OAs and guide them in doing tasks, deliver items with its arm and participate in games for entertainment. Additionally, this robot can recognize human gestures and speech, detect humans and speak with users [42,47]. These features, combined with facial expressions, have improved its ability to interact with humans.

The last generation of Care-O-bot consists of an omnidirectional platform with a touch screen on the head. Moreover, it is equipped with stereo cameras and a 3D sensor that helps the robot explore the environment easily [48]. The Care-O-bot 4 is a Robot Operating System (ROS)-based robot with hardware modularity, and in the third version, they installed a tray to carry objects safely. This robot has two seven-degree-of-freedom (DoF) arms with two-DoF grippers, while the torso and the head can have either one or three DOFs each [49].

Since the Care-O-bot project has been active for more than 20 years, application examples are plentiful. Some papers focused on the explanation of first [50], second [51], third [52] and fourth [44] versions of Care-O-bot's configuration. In the first two versions, the OAs could use this robot as an intelligent walking aid system [53], and although there were some technical limitations, the users were satisfied [54]. Because of the vast capabilities of Care-O-bot 3, it was tested on various occasions [42,47,55,56]. The practical evaluation of Care-O-bot 3 demonstrated its high acceptance between care workers and OAs [46], while they believed that the current robot had some limitations [57]. Moreover, the engagement of Care-O-bot 4 with participants in various tasks was investigated and users perceived the robot as an assistant even though they believed it had limitations [48].

3.2. Robovie

The Robovie is a human-like robot designed by Advanced Telecommunications Research Institute (ATR) in Japan to communicate properly with humans. The platform of Robovie-II consists of 2 arms, 16 skin sensors, 24 ultrasonic sensors for obstacle detection, 10 tactile sensors, 2 microphones and vision sensors. This generation can work for four hours, and its eyes have a pan–tilt mechanism suitable for stereo vision and gazing control [58,59]. The Robovie-II robot is represented in Figure 3.

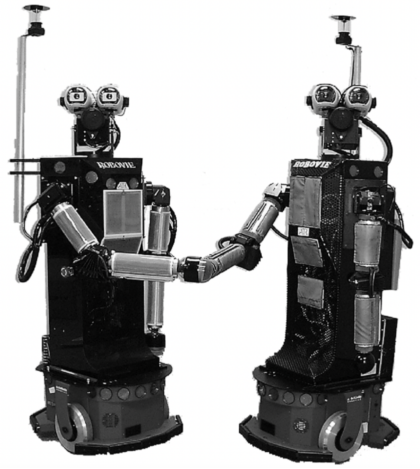


Figure 3. The Robovie-II [58].

The application domains of the Robovie are extensive, including social isolation problems, daily greeting, chatting, encouraging OAs in complex tasks, helping in the supermarket, indicating shop locations in a mall, etc. [26,60]. The Robovie is able to interact with humans by speaking and gesturing, behaving like a human child, and moving eyes or head to represent meaningful behaviours [58].

Research has been accomplished to assess the advantages and drawbacks of the Robovie. For example, this robot was placed for more than three months in an elderly care centre to observe the interactions of OAs and staff with it [61]. Although the robot was remotely controlled and had some limitations, OAs and staff could accept it into their community. A qualitative study on the acceptance rate of visitors regarding social robots was reported in [60] using Robovie-II. After three years in a local shopping mall in Japan, the overall opinion towards this robot and its abilities was affirmative. Furthermore, for two months, the visitors of a science museum evaluated the Robovie-II with high positive scores [62]. Moreover, users expressed enjoyment through the chatting and emotional support of the robot [58]. The relationships between negative attitudes and HRI were experimented, and two psychological scales were developed: the Negative Attitudes toward Robots Scale (NARS) and the Robot Anxiety Scale (RAS) [63]. The results revealed that negative attitudes in these scales predicted subject communication avoidance behaviours in HRI. In addition, there were some gender differences between negative features and communication avoidance behaviours toward the robot.

3.3. Pearl

The project of Pearl as an autonomous mobile robot was started under the Nursebot project at Carnegie Mellon University in order to respond to seniors' daily challenges such as reminding and environmental guidance [64]. Figure 4 shows the Pearl robot. This robot can navigate autonomously, recognize speech, detect faces and compress images for better online video streaming [65,66]. The users interact with Pearl via speech and a touch-screen graphical display [67].

On the hardware side, the platform of this robot comprises a differential drive system, two onboard Pentium PCs, wireless Ethernet, laser rangefinder, sonar sensors, microphones for speech recognition, speakers for speech synthesis, stereo camera, graphical displays, two sturdy handle-bars and a removable tray [65,68]. Moreover, the Pearl is equipped with Autominder, a reminder software system for daily plans and schedules. Autominder monitors the execution of activities, and then it can detect the difference between the expected activity and the one that is carried out [20,69]. The software system did not use a camera due to the complexity of the process (At the time when this robot was designed, processing a high quantity of data was not as fast as currently.)and privacy issues [20].

Figure 4. The Pearl robot [29].

The assessment of Pearl based on appearance and social behaviour revealed that these factors influenced people's perceptions and willingness to use a robot [70]. Furthermore, the practical test of Pearl in an actual environment with OAs showed its robustness and feasibility of use. However, adapting the initial velocity to the user's walking pace and voice level was challenging [65,67].

3.4. Personal Robot 2 (PR2)

The PR2 is a versatile human-assisting mobile manipulating robot created by Willow Garage based in the United States. This ROS-based robot is designed to provide independent living for humans, especially seniors, and interact with them. Aside from a high level of interaction, PR2 can perceive the environment in 3D, and this factor helps it navigate autonomously [71]. Moreover, thanks to compliant arms, it can perform tasks such as walking dogs, folding clothes, opening doors and other similar works [40]. The first generation of this robot (i.e., PR1) had similar features to PR2. Both generations are shown in Figure 5.

Figure 5. The PR1 (**left**) [72] and PR2 (**right**) [73].

The PR2 is equipped with an omnidirectional wheeled base, a telescopic torso, two eight-DoF arms with a one-DoF gripper on each arm, a pan–tilt head with two stereo cameras and a LED projector [71,74]. The PR2 has been used in multiple home assistance projects, from being a cookies baker [74] to a dressing assistant [75] or a drink fetching application along with a new task-level executive system (i.e., SMACH [76]). The latter research aimed to identify critical issues in the autonomous robotic assistant area. Moreover, a similar study was implemented to figure out its performance in a real home with people with disabilities [77]. The change in the attitude of the elderly toward PR2 when they perceived its capability was also described, showing a better acceptance after the demonstration [78]. An exhaustive study about OAs' preferences and attitudes toward a SAR such as the PR2 was conducted [79]. The results from this study's interviews and questionnaires showed that OA users were interested in robots for tasks such as chores, information management and moving objects. However, for personal care, they preferred human assistance.

3.5. Bandit

Bandit is a humanoid torso mounted on a wheeled platform created by the University of Southern California Interaction Lab and BlueSky Robotics (see Figure 6). Encouraging OAs for physical exercises and providing cognitive training can be considered the prominent roles of Bandit [41]. Moreover, this robot interacts with OAs to reduce their social isolation and lack of recreation [26]. The Bandit's platform consists of a torso with 22 controllable DoFs (hands, arms, eyebrows, waist, neck and mouth), a speaker, camera and laser rangefinder [80]. The camera is located at the waist for capturing actual human movements, and in combination with a prerecorded speech (generated by NeoSpeech engine), the Bandit can give feedback to users [81].

Figure 6. The Bandit II robot [82].

Some exciting features of the robot have made it suitable for research on HRI or imitation learning (IL) [26]. Tapus et al. tried to evaluate the role of Bandit in establishing an efficient interaction with OAs who had dementia or other cognitive impairments through a specific music-based cognitive game [80]. The results of six months of interactions demonstrated that the OAs' attention to music improved or was sustained across an extended period. Moreover, three exercise games based on gestures were considered, including a workout game, a imitation game and a memory game [82]. After two detailed assessments, the overall reaction of users toward using Bandit was enjoyable and helpful. Fasola et al. evaluated the effectiveness of Bandit across the motivation and engagement of elderly users in physical exercise. The result of a study on 33 participants validated the user's preference for the physical robot embodiment over the virtual robot embodiment. In addition, the participants rated their experience with this robot coach as enjoyable, valuable and socially attractive [83].

3.6. Kompaï

Kompaï is a social assistive mobile platform designed in three versions by KOMPAÏ robotics based in France (see Figure 7). This robot supports independent living and sociability for OAs [84]. The Kompaï robot provides miscellaneous services: day and night surveillance, mobility assistance, fall detection, shopping list management, agenda, social connectivity, cognitive stimulation and health monitoring [37,85]. The Kompaï robot can also recognize speech, navigate through unknown environments, avoid obstacles and detect risky situations [39,86]. Users interact with the robot via a touch screen and voice, and it is equipped with a small handle to help the elderly rise. Kompaï's third version platform was improved to be more user-friendly [87].

Figure 7. Kompaï robots: (**left**) 2009, (**middle**) 2016, (**right**) 2019 [87].

The Kompaï robot is a popular service robot that has been used in various projects such as ENRICHME [88] or on different occasions such as in restaurants [89] and OAs' houses [86]. An exploratory study revealed the requirements of users in interaction with this robot [90], and they considered adaptivity, long-term autonomy of operation, user-friendliness as well as low costs as essential factors [91].

Moreover, OAs considered Kompaï as part of their safety system [92], and entertainment was considered an exciting feature [86]. In contrast, after one-month interactions with Kompaï, OAs demonstrated low intention in using the robot while perceiving it as amusing and not threatening [39]. In order to evaluate the role of graphical user interfaces (GUI) in HRI, two different applications (a shopping list and an agenda) were considered [84]. Results showed that one's cognitive profile and computer experience influenced the speed of learning and using robot interfaces appropriately.

3.7. HealthBot

The HealthBots project is a large-scale joint project between the University of Auckland, Electronics and Telecommunications Research Institute (ETRI) and Yujin Robot. The development of admissible healthcare robots for the ageing population and caregivers was the primary goal of this project. The researchers of HealthBots tried to design a multipurpose service robot. This robot can be used as medication [93] or schedule [94] reminder, a detector of possible falls through a ZigBee network [95], an entertainer or memory assistant [96] and a telephone caller [97]. Moreover, the HealthBot measures vital signs such as blood pressure, arterial stiffness, pulse rate, blood oxygen saturation and blood glucose levels [97]. Figure 8 shows the last version of HealthBot.

Figure 8. The HealthBot [98].

The HealthBot is a differential drive mobile robot powered by a 24 V lithium–polymer battery. It comes with a dedicated software platform, and from the hardware point of view, this robot consists of two single-board computers, a tray for carrying medication, a laser rangefinder, sonar sensors, bumper sensors, microphones, speakers, a touch screen, a camera, and Universal Serial Bus (USB) ports [95,97]. The HealthBot interacts with users through speech, visually, a touch screen and movements [99].

The HealthBot has received a high acceptance rating among OAs and staff of a retirement centre [94,96,97,100,101]. Overall, the participants showed a positive tendency towards healthcare robots in these empirical research studies. Furthermore, different aspects of the robot, such as medication reminder application [93], reliability based on interaction via synthesized speech and touch screen [102], entertainment services (music videos, quotes, and pictures) [99], robot system and the software framework [95] were assessed in other studies. Users perceived the robot as easy to use and felt confident about it [93]. The influence of entertainment on the usage time of robots and users' desires was also considered [99]. Chandimal Jayawardena et al. confirmed the robustness and scalability of the software framework along with the robot system through two case studies in a retirement village in New Zealand [95].

3.8. SCITOS

The SCITOS A5 robot is a notable service robot produced by MetraLabs based in Germany, and it is used in the STRANDS Project. This project's main objective is to design intelligent mobile robots for long-term operation (up to 18 h with six hours of charge [103]). Figure 9 shows the SCITOS robot. SCITOS is a multifunctional robot for social communication, using in care centres [104] or for public tasks [105]. In addition to service and entertainment, it can be a physical therapist for OAs with dementia [106] and a supporter of security and surveillance [103].

This robot can interact with users via speech synthesis, a touch screen and head motions. Moreover, the exploration of the environment is possible through autonomous navigation and 3D obstacle avoidance [103]. SCITOS provides entertainment programs for all ages, and with a panorama view, it is capable of human detection and tracking, object recognition and 3D spatiotemporal mapping. It is equipped with frontal cameras (two ASUS Xtion RGB-D cameras at the chest and head) and safety SICK S300 lasers in the base [104,105]. Another exciting feature of the robot is its frequency map enhancement (FreMEn) component that assists it in coping with environmental changes [107].

For the evaluation of the robot, field studies were conducted. To give an example, the SCITOS A5 robot was used as a companion for physical therapy walking groups of OAs with advanced dementia [108]. Although some technical problems occurred during prolonged usage, the opinion of therapists about this robot was positive. At first sight, OAs did not interact with SCITOS, but therapists could engage the participants in using it. Similarly, Hebesberger et al. [109] focused on deploying SCITOS at a care hospital for OAs with severe multimorbidity and dementia. The outcomes of this study showed that all employees, visitors and residents were interested in interacting with the robot. However, half of the employees stated that they would not want to share their workspace with a robot. According to the paper, a possible reason was that robots could be a threat to jobs and take them away. The question of how elderly with dementia used the SCITOS as a physical therapy companion was investigated [106]. The results showed that most of the interactions were encouraged by the therapists instead of being self-induced; hence, OAs with progressed dementia required the guidance of a therapist.

Figure 9. The SCITOS A5 robot [103].

3.9. Pepper

Pepper is a prolonged autonomous semihumanoid SAR from SoftBank Robotics (formerly Aldebaran Robotics) based in Japan and France, (see Figure 10). This robot was developed for a large number of domains such as cognitive training, health monitoring, companionship, schedule reminding, greeting, conversation, conducting surveys, educational purposes, entertainment, autism therapies [24,110,111] and even screening staff members during the COVID-19 pandemic [112].

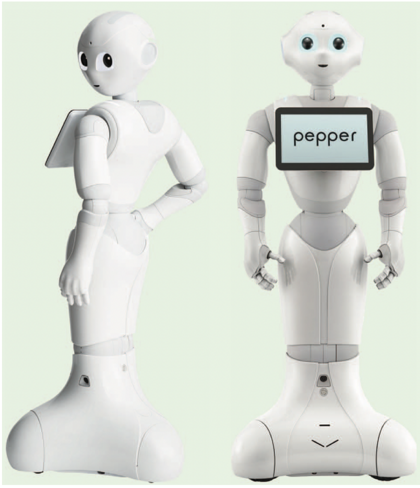


Figure 10. The SoftBank Robotics Pepper robot [24].

Moreover, Pepper has the capabilities of speech and emotional recognition, localization of sounds, safe navigation, exhibiting body language and interacting with the environment through perception modules [24,113].

Pepper has omnidirectional wheels and a humanoid body on which sonar, laser and bumper sensors are mounted. Its platform is designed without any sharp edges to be safer. Furthermore, it is equipped with a touch display with a gyroscope on the torso, two RGB cameras, a depth camera, a six-axis inertial measurement unit (IMU), two speakers, four microphones, two tactile sensors on the hands, two ultrasonic sensors and a high-capacity battery working for approximately 12 h. The Pepper robot has a total of 20 DoFs and uses the NAOqi proprietary software platform [24,114].

Aside from its diverse abilities, Pepper is a fully programmable platform. For example, Yang et al. [115] applied reinforcement learning (RL) and human feedback to improve the robot's ability in task execution. Furthermore, a modified version of this robot was presented with the name of PHysical Assistant RObot System (PHAROS) [116,117] that was planned to assist OAs in their daily activities and recommend and monitor physical activity exercises. The platform of PHAROS consists of three main sections: a Pepper platform, human exercise recognition through DL methods for exercise monitoring and the Recommender, a smart-decision maker for recommendation of the most suitable physical exercises with respect to the user's physical limitations. Figure 11 shows a view of PHAROS software and hardware.

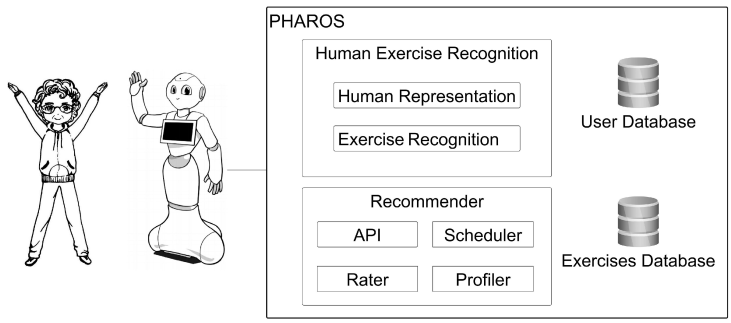


Figure 11. The PHAROS architecture [117].

In general, the acceptance rate of Pepper and PHAROS was considerable. Gardecki et al. [113] summarized the practical aspects of working with Pepper. After a 10-week interaction with Pepper in a residential care home, the OAs gave positive feedback to it [118]. However, they declared this robot would not replace care-givers. Similarly, participants in a dedicated questionnaire about the influence of social robots on seniors considered Pepper as an acceptable assistant [119]. In another pilot study [120], Pepper was used to encouraging OAs to walk more. Although the number of participants was few, the results of trust, interest and usefulness were acceptable. Thus, this study proved that robots such as Pepper could be companions and motivators for OAs. Beraldo et al. [121] explored the relationship between human gender and a social robot (using Pepper) regarding perception and task expectation. The results demonstrated that both men and women perceived Pepper as male (or neutral) and a kind machine. Moreover, a pilot study to validate PHAROS performance illustrated user satisfaction with the system [116].

3.10. RAMCIP

RAMCIP (Robotic Assistant for MCI Patients) is a service robot that provides safe and proactive daily assistance to the ageing population, especially those with memory impairments. This project is coordinated by the Centre for Research and Technology Hellas in Greece under EU Horizon 2020 program [122]. RAMCIP can be used in a vast number of categories of tasks consisting of emergencies (fall detection and gas/smoke detection), assistance in keeping the home safe (turning off electric appliances such as an oven or turning on lamps for locomotion), communication with relatives and friends, reminding to take medication, supporting in food preparation and picking up fallen objects [123,124]. Two versions of the RAMCIP robot are shown in Figure 12.

Figure 12. The first (**left**) and second (**right**) versions of RAMCIP [125].

The software program has three main modules: perception, action and cognitive functionalities. The perception module provides environment hierarchical semantic mapping (RGBD-SLAM), object detection and state tracking and human monitoring (RGB-D skeleton and laser-based leg tracking along with action recognition). Navigation, manipulation and grasping relate to the action module. The last module governs the task planning and decision-making policy [125]. Moreover, the platform of RAMCIP encompasses a two-DoF mobile platform, an elevation mechanism for changing height, a five-DoF arm manipulator with a two-DoF wrist, a two-DoF head with a mounted display for facial expressions, an RGB-D camera, two laser scanners and speech synthesis technology [125,126].

The RAMCIP project was evaluated in various situations such as real-house environments with MCI patients [125], clinics with patients suffering from MCI or Alzheimer's disease (AD) [127], and its user interface (UI) framework was also studied [128]. The pilot trials indicated that RAMCIP could accomplish its core tasks and assist OAs, although users initially doubted its performance [125]. The robot's acceptability in hazardous events with 18 old participants revealed its appropriate societal impact and usability score [127].

The RAMCIP's expression of emotions (facial expression and speech intonation) and its impact on design was an exciting matter [126]. The interaction of users with the robot in this regard yielded encouraging outcomes. In addition to their novel approach for automatic human action recognition with skeleton joints information [129], an innovative skills assessment methodology was developed to enhance the robot's awareness of the user's perceptual and cognitive skills [124]. The results showed that the cognitive capabilities of the robot were sufficient to obtain precision skills.

3.11. Hobbit

The Hobbit mobile service robot is a research project of the EU's 7th Framework Programme that the Vienna University of Technology designed. The Hobbit project addresses some prominent issues in OAs' lives, including reducing loneliness, helping with domestic tasks and providing medical and social assistance [130]. Thus, the main applications of the Hobbit are supporting independent living, delivering services, recognizing users' instability such as falls, handling an emergency, reminding users of tasks, entertainment or cognitive exercises [114,131]. The valuable lessons of this project regarding design and practical tests were presented in [130,131]. Figure 13 shows the last prototype of the Hobbit robot.

Figure 13. The Hobbit robot [130].

The mobile platform of the Hobbit consists of a six-DoF arm with a two-finger gripper. For precise navigation and detection, it is equipped with a depth camera (facing downward), an RGB-D camera, eight infrared and eight ultrasound distance sensors and two bumpers. Moreover, there is a multimodal user interface (MMUI) for human interactions or task execution. The user can interact with the robot via a wireless call button, automatic speech recognition or gesture recognition interfaces and a touchscreen [131,132]. With its sensors, it has the abilities of safe navigation through the environment, human detection and tracking, object detection (learning and picking up from the floor), automatic recharging, gesture recognition, transport objects and speech recognition [130,131].

This project was tested in various situations and countries such as Austria, Greece and Sweden to highlight the functionality, safety and operational features that an OA requires [133]. Even though there were several technical malfunctions during the field trial, the participants in [130–132] declared that interaction with the Hobbit was easy and this robot was acceptable. Moreover, they considered picking up objects from the floor as the most helpful household functionality [130]. Results in [132] highlighted that users believed the Hobbit would be a part of future elderly care. While this robot could meet the users' expectations, they did not assume the robot to be a supporter of independent living or safety at home [134]. Similar outcomes were presented in [135] in addition to the design process of the robot.

3.12. TIAGo and ARI

PAL Robotics, based in Spain, designed the TIAGo and ARI robots for indoor applications as caring assistants or as open-source platforms for research projects. TIAGo is a mobile service robot whose notable features allow it to perform a wide range of tasks such as navigation, manipulation, perception, interaction and motion planning [136]. In addition, ARI is a mobile humanoid service robot whose primary design goals are enhancing user acceptability regarding social robots [137] and adopting AI algorithms for caring purposes [11]. Figure 14 shows the latest versions of both robots.

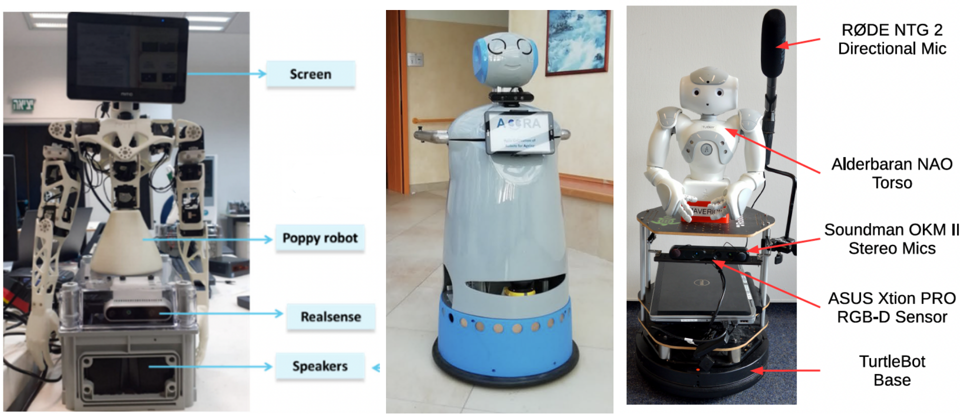
Figure 14. TIAGo (**left**) [136] and ARI (**right**) [137] from PAL Robotics.

TIAGo and ARI are ROS-based platforms that can be extended for different objectives such as imitation learning (IL), deep learning (DL), motion planning, etc. They are equipped with fundamental environmental perception, learning, navigation and obstacle avoidance abilities. The ARI platform consists of a mobile base, a Linux based tablet on the torso, an RGB-D head camera, an RGB-D torso camera, two speakers, four microphones, two optional four-DoF arms [138] and a thermal camera when it is used for COVID-19 screening [139]. Moreover, the TIAGo has customizable lidar and sonar sensors, an RGB-D camera on the head, a speaker, two microphones, a seven-DoF arm and some accessories such as a thermal camera [136,140].

These robot platforms have been used in several research projects. The ENRICHME is one instance of using TIAGo to develop a SAR for helping the elderly, adapting to their needs and having a natural behaviour [5]. In this project, the assistive robot reminded OAs of events and aided them with physiological monitoring, cognitive training, social connectivity and object finding thanks to integrated radiofrequency identification (RFID) technology and sensors [28,141]. From the HRI perspective, OAs perceived the TIAGo robot as a trustable agent that could be used easily [142]. Furthermore, results in [143] revealed the high impact of text or verbal interaction between the robot and the participants. Roa et al. presented a technical description of the Mobile Manipulation Hackathon held at the International Conference on Intelligent Robots and Systems (IROS) 2018 [144]. In this competition, the finalist teams used TIAGo as the research mobile manipulator for various tasks such as IL, item placing, liquid pouring and serving drinks as services for OAs. Moreover, the ongoing SHAPES project uses ARI to extend digital solutions for the healthy and independent living of OAs [145]. The ARI robot was evaluated in residential care in Spain as the third phase of the SHAPES project [146]. This phase was conducted with five aged participants to investigate the robot's functionality and user acceptance. Although some OAs were uncomfortable with eye movement, general attitudes were positive toward ARI. However, it concluded that this robot should be more customized to the user. Due to using a set of multimodal communications in ARI [139], it was a suitable candidate for COVID-19 applications [147] or the integration of digital technologies for supporting the independent living of OAs [145].

3.13. Other Robots

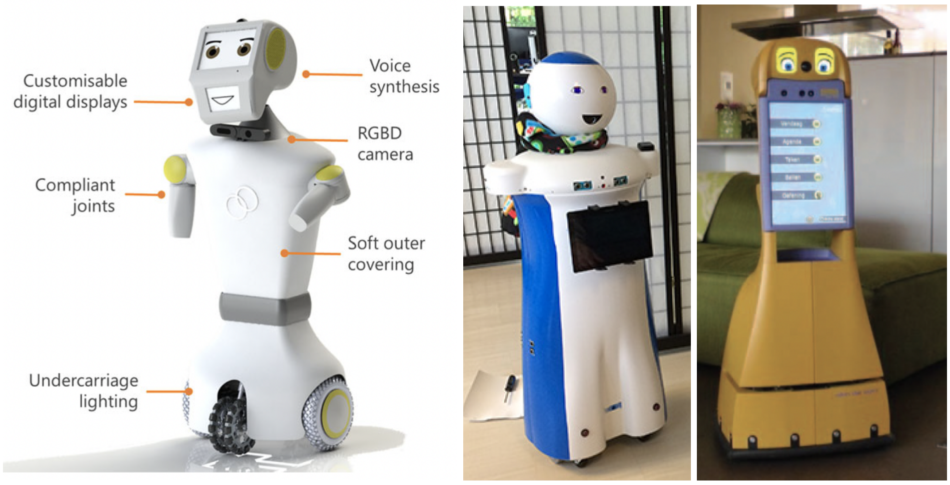
In this section, some mobile assistive robots are reviewed summarily due to the paucity of proper documentation or limited applications. These robots are designed for elderly life or can be used in this regard. As an example, robots such as Gymmy [148] or ASTRO [9] have been used for physical or cognitive training of OAs. Although the Gymmy robot focuses mainly on upper-body activities, almost all users were satisfied with it, and they would like to use it in the future. The main applications of ASTRO are supporting OAs in their indoor walking activity and guiding them in physical training. The platform of the ASTRO robot is based on SCITOS G5, and surveys from OAs partially confirmed its effectiveness [149]. Furthermore, IRMA [150] is a robot for finding misplaced objects that can be used for OAs too. The IRMA is an NAO torso-based robot consisting of navigation, perception and communication layers with a wide range of capabilities. All mentioned robots are shown in Figure 15.



(**a**) (**b**) (**c**)

Figure 15. (**a**) Gymmy [148], (**b**) ASTRO [9], and (**c**) IRMA [150].

Another SAR that was developed in two versions and used the design thinking philosophy is Stevie (see Figure 16a). This robot aims for the long-term care of OAs and people with disabilities. Stevie is equipped with a human-inspired torso and two short arms [151]. Some of its functionality consists of verbal communication, medicine reminding, cognitive training and forming gestures [152]. McGinn et al. [151] evaluated the prototype of Stevie at a retirement centre with the presence of residents and care staff. The outcomes of this experiment demonstrated a positive attitude toward this robot regarding design, usability and technology. Moreover, the impact of the Stevie robot in a day centre for OAs with dementia was investigated to explore staff views [152]. This robot was deployed in this centre for two weeks, and 40 guests with dementia participated. Staff reported that the guests' engagement with Stevie was promising and that they enjoyed it, and the staff could interact longer with guests or attend to other duties.



(**a**) (**b**) (**c**)

Figure 16. (**a**) Stevie [151], (**b**) Rudy [111] and (**c**) Max [153].

Rudy, an AI-enabled mobile robot, is a similar solution to assist the elderly community. This robot provides remote monitoring, medicine reminding, fall detection/prevention and social connectivity using machine learning algorithms [154]. Figure 16b shows the Rudy robot. Max is actually a companion robot developed for long-term assistance of OAs at home [153]. Although the Max robot is not a mobile manipulator, it can accomplish a myriad of tasks such as user detection/tracking, fall detection, reminding and cognitive training thanks to various sensors and a control architecture [155]. Figure 16c shows the Max robot.

On the other side, household robot assistants such as MOVAID [17] or assistive kitchen systems such as Casper [156] can be used in elderly homes. Since Casper is equipped with an expressive face and arm gestures, its level of engagement was high [157], which positively affected OAs even with a novel learning architecture [158]. While robots such as Sanbot Elf [159] and James [114] cannot help OAs in household tasks, they have the ability to monitor the environment. One of the applications of the Sanbot Elf and James robots is detecting fallen people with pretrained convolutional neural network (CNN) and helping OAs keep their contact with family and friends, especially during the COVID-19 pandemic [160], respectively. Moreover, CHARMIE [161] is a newly designed generic robot for various purposes in homes, domestic houses and healthcare facilities. This robot has numerous advantages for OAs, but it is a new project with inadequate publications.

A group of mobile manipulators can be used for nursing care or as personal assistants; hence, they can perform appropriately in OAs' lives. This category comprises robots such as Lio [162], Robot SAM [163] and ARNA [164] that combine arm and mobile wheel-based platforms. Lio can complete various tasks such as care applications, delivering items, autonomous navigation and charging, entertaining and motivating users, recognizing and greeting people, interacting by touch/voice and reminding of upcoming appointments. ARNA is capable of fulfilling a range of tasks with its arm, and some novelties in software architecture, interfaces and sensing instrument protocol cause it to be a suitable robot for indoor nursing applications. The ARMEN project used robot SAM to provide advanced functionality for OAs at home. This one-arm robot can navigate autonomously, recognize objects and speech, detect emotions and manipulate objects.

Summary of Robots

This section outlines the technological foundation of all mentioned mobile service robots in a table format. Since some robots have old technology (e.g., Pearl), are used in commercials (e.g., Pepper) or for specific applications (e.g., Bandit), their straightforward comparison is challenging; hence, this table is presented solely for a quick overview.

In Table 2, the mobile robots in Section 3.13 are ignored due to inadequate documentation or practical studies. Moreover, TIAGo or ARI are actually a robotics research platform that can be improved in functionality. However, the primary features of these robots are considered based on company datasheets.

Table 2 shows the mobile service robots that provide extender applications for OAs such as Hobbit, Pepper, RAMCIP, Care-O-bot, ARI and Kompaï. Moreover, it demonstrates that Hobbit, Pepper, ARI and TIAGo provide more functionality for OAs. It was expected that commercial mobile service robots such as Pepper, Kompaï and Care-O-bot would receive the highest credit in general. Other results of the table that align with the proposed analysis in [165] relate to the camera, the most used sensor in SARs, and speech, which is the second way of social interaction.

Another parameter that can be determined is the technology readiness level (TRL) for estimating the maturity of technologies. Since most mobile service robots come from research projects, assessing their exact TRL is complicated, and there is no valid documentation for that. However, we believe these research projects could be classified between TRL four and six in the yellow category. For commercial robots, such as Care-O-bot, this value would be in the green zone between seven and nine.

Table 2. Summary of mobile service robots applications: (a) social communication, (b) emergency detection, (c) object manipulation, (d) reminding, (e) entertainment, (f) trainer, (g) health monitoring and functions, (h) autonomous navigation, (i) human detection, (j) object detection, (k) speech recognition, (l) ML algorithms and (m) autonomous recharging.

Robotic Platform	**Applications**							**Functions**					
	(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**(j)**	**(k)**	**(l)**	**(m)**
Hobbit	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Pepper	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RAMCIP	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
Kompaï	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓
Care-O-bot	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
SCITOS	✓	✓			✓	✓		✓	✓	✓	✓		✓
TIAGo	✓		✓					✓	✓	✓	✓	✓	✓
ARI	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pearl	✓			✓			✓	✓	✓		✓		
Bandit	✓			✓		✓			✓		✓		
HealthBot	✓	✓		✓	✓		✓	✓	✓		✓		
PR2			✓				✓	✓	✓	✓			
Robovie	✓				✓	✓		✓	✓	✓	✓		✓

4. Discussion

The mainstream research and practices in mobile service robots were identified in this review paper. This section discusses current challenges and recommendations which may be helpful for the community and may be used in future research around mobile service robots for OAs care.

Since mobile service robots perform their tasks in close contact with OAs, it is crucial to consider safety requirements [166]. The collision between the robot and an OA or the malfunction of the robot may occur in the context of HRI. Thus, developers should improve their knowledge about mobile service robot safety issues, especially for elderly care. Generally, there should be a high degree of trust between the OAs and the robot for broad acceptance. Thus, privacy and security should be essential factors to be considered when designing such robots [167]. When OAs are unaware of the quantity of private data a mobile service robot is collecting or whether a third party is accessing their data, it is very challenging to trust a new technology. User privacy can be improved by:

- The optimal design of the robot;
- Clear communication between the OA and robot [168];

- Straightforward explanations before a performance;
- Decreasing the number of sensors in the environment.

Moreover, the technical part of the robot's security needs to improve at the point of failure for recovery against cyberattacks [169].

A common issue in many field studies relates to their short-term HRI [38,170]. Ideally, studies must be long-term in an actual deployment environment to investigate sufficiently the impact of mobile service robots and repeated interactions on OAs' lives. In the prolonged performance of service robots, some features may be more vital such as the mobile robot's design, ease of use, the technology behind the robot and ethical issues. The mobile service robots need a pleasant physical appearance and optimized design regarding size, weight, body expressions and gestures [171,172]. Although there is a widespread concern between caregivers and OAs toward the replacement of humans with service robots, their design should develop to play a more profound role in elderly life. Therefore, the design of service robots should consider the culture, language (in verbal communication), personality of aged people and even contact with them [172]. A robotic arm can be used in multiple ways of intervention, but its performance depends on some complex functionalities such as object detection, human gesture recognition and so on. Thus, using arm(s) in mobile service robots is uncommon or limited, and it is a challenging problem in robot design [43].

Another factor for diminishing technophobia in OAs is quickly learning how to interact with and control the mobile robot. Over the years, robotics solutions, especially mobile robots, have followed their technical path. However, new designs should involve modern technologies in the robot's functionalities to provide a bidirectional data exchange between the mobile robot's platform and smart devices [43]. There should be a balance between applying high technologies and considering the ease of use [173]. Unfortunately, the readiness of novel technologies in mobile service robots is still challenging, and many functions are considered predefined. In the near future, mobile robots' online learning should develop more to bring broader reasoning about the elderly environment [174]. Moreover, with respect to novel technologies and AI methods, researchers should improve the mobile service robots to provide personal care for OAs. In other words, the human-centred care approach is a missing element in the puzzle of SAR to support independent living from the viewpoint of an OA [175,176].

The limitations of current technology in SARs prevent going deep into the topic of ethics and cost. There is a potential ethical concern about the long-term usage of mobile service robots in the OAs' environment. The ethical issue is, in fact, a part of the design, and it requires an extended investigation beyond this paper [177,178]. The ethical challenges can be hidden in privacy, safety, dehumanization and false or inadequate training in AI algorithms. These challenges can also be noticeable in terms of social deprivation, emotional deception, disempowerment and emotional attachment, especially regarding vulnerable users [179]. The last aspect of mobile service robots that plays a significant role in their commercialization is cost. Affordability accelerates mobile service robots' usage rate at homes or care centres [173]. The final costs of mobile manipulators need to be reduced considerably even though they have faced high-cost reductions in the last years due to advanced technologies.

5. Conclusions

The world population is ageing, especially in developed countries. To address this looming issue, recent studies have been working on assistive technologies such as SARs. One subgroup of SARs is mobile service robots, which have shown a high potential in supporting the independent living of OAs. In this paper, we reviewed mobile service robots used in aged care from 1999 to 2022 with the viewpoint of applications and field studies.

The results represent that the overall OAs' attitude toward using mobile service robots is promising, and it can be expected that such robots will play a profound role in aged care. However, there are some challenges or unsolved issues that should be considered in the design of mobile service robots. Safety is essential for elderly users because they are in close contact with robots. Moreover, since robots record numerous environmental parameters, they should guarantee personal privacy for aged users by decreasing the number of sensors or providing clear explanations before usage. Moreover, ethical and affordability matters should be considered in higher levels in future designs.

Besides the mentioned challenges, some issues are common in field studies. Practical tests need a longer time to better assess mobile service robots' influence on OAs' lives. Mobile service robots should take into account the user's cultural factors and have a pleasant physical appearance. In addition, human-centred care options would be a hot topic for providing service to OAs. The balance between applying high-level technologies and being user-friendly is another critical matter that should be considered for future works.

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