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Review

Service Robots: A Systematic Literature Review

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Abstract: A service robot performs various professional services and domestic/personal services useful for organizations and humans in many application domains. Currently, the service robot industry is growing rapidly along with the technological advances of the Fourth Industrial Revolution. In light of the great interest and potential of service robots, this study conducts a systematic review of the past and current research in service robots. This study examines the development activities for service robots across applications and industries and categorizes the service robots into four types The categorization provides us with insights into the unique research activities and practices in each category of service robots. Then, this study analyzes the technological foundation that applies to all four categories of service robots. Finally, this study discusses opportunities and challenges that are understudied but potentially important for the future research of service robots.

Keywords: robots; service robots; human-robot interaction; framework; social robots; professional robots; domestic robots

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1. Introduction

Service robots are a type of robot typically used outside of industrial settings. Service organizations are increasingly introducing robots to frontline services [1]. The research of service robots is gaining momentum, and different definitions have been proposed to describe service robots. For example, The International Federation of Robotics [2] defines service robots as those "that perform useful tasks for humans or equipment excluding industrial automation applications." Wirtz et al. [3] define them as "system-based autonomous and adaptable interfaces that interact, communicate and deliver service to an organization's customers." A service robot has not only technological features for services but also the ability to engage in human interactions [4]. Service robots have been advancing rapidly along with the advances in computer vision, speech recognition, sensors, and artificial intelligence. Innovations in sensors, navigational systems, and machine learning are making robots smarter, more mobile, and less expensive for a wider range of services which are often carried out in dynamic environments, requiring capabilities for navigating through populated and sometimes restricted areas [5].

Service robots have many potential benefits such as improved productivity, consistent service quality, and reduced staffing costs. Service robots enable enterprises to rapidly collect data from the environment, analyze the data on the fly, and serve the changing needs of the customers promptly. Some examples are intelligent robot wheelchairs, surveillance drones, education robots, therapy robots, entertainment robots, and self-driving cars. According to Gartner Hype Cycle 2019 in artificial intelligence [6], smart robotics is on the rapid rise and is expected to reach a plateau in 5 to 10 years when the technology will be widely diffused. Part of the cost-saving from the adoption of service robots can be realized from automation and labor substitution [7].

The prospect of robot market growth is very strong. According to MarketsandMarkets [8], the service robotics market is expected to grow from USD 37.0 billion in 2020 to USD 102.5 billion by 2025 at a compound annual growth rate of 22.6%. According to a

Brookings Institution survey [9], 52 percent of 2,021 adult Internet users feel robots will perform most human activities and 94% of those who have adopted robots say that robots increased productivity in their business.

Industrial robots have been widely deployed for various manufacturing tasks including hazardous material handling, dangerous operations, and machine monitoring and operations. On the other hand, service robots are deployed for specific service functions. Service robots show substantial opportunities to increase productivity and reduce costs [4]. Consumers are more frequently faced with options of human and robot services in the hospitality industry and have a more positive attitude toward robot-staffed hotels when COVID-19 is a major threat to public health [10]. With the widespread use of robots and artificial intelligence, there have been ongoing discussions among researchers and practitioners on the impact of robots on the labor market and economy due to their potential to replace human jobs and labor [10].

Most studies on service robots have focused on narrowly defined technical issues and human perceptions of service robots. While there are several efforts at a literature review on service robots [4,11–13], there is a lack of a comprehensive systematic literature review of service robots based on the integrative view on service robot types and the technological foundation of service robots. In light of the current gap in the literature review, this paper focuses on a systematic literature review of various professional and domestic/personal service robots. The selected papers were analyzed to develop high-level perspectives that have guided service robot research. The unique contribution of this article is to (1) review service robot applications and research in a variety of applications and domains, (2) categorize service robots to have an in-depth understanding of state-of-the-art technologies in each category, (3) review the technological foundation of the service robot applications, and (4) discuss challenges and opportunities in service robot research.

This paper consists of nine sections: (1) introduction, (2) methodology of the systematic literature review, (3) discussion of professional non-social service robots, (4) professional social service robots, (5) domestic/personal non-social service robots, (6) domestic/personal social service robots, (7) discussion of technological foundation of service robots, (8) discussion of challenges and opportunities of service robots research, and (9) conclusion.

2. Methodology for Survey of Service Robot Research

To conduct a systematic literature review, this paper follows a systematic literature review methodology suggested by Kitchenham et al. [14] and the PRISMA 2020 statement [15]. A systematic literature review is aimed at achieving a synthesis of scientific research on a specific topic through a rigorous analysis of past and current studies. The typical steps in the systematic literature review method include: (1) research questions, (2) search process, (3) inclusion/exclusion criteria, (4) quality assessment, (5) data collection, and (6) data analysis [14]. This study uses the aforementioned steps as a guide for the systematic literature review.

2.1. Research Questions

There is a paucity of studies in the form of a literature review on service robots due to the relatively short history and the interdisciplinary nature of service robot application development. Previous literature reviews are broadly categorized into technology focus and human/managerial focus. For example, Kahraman et al. [12] conducted a comprehensive literature review on the recent technological developments and theories in fuzzy set models for humanoid robots. While the use of fuzzy sets is helpful for the development of humanoid robots, they noted that the existing fuzzy set models are not enough to properly model complex human behaviors.

To understand human/managerial aspects of service robots, a three-part framework was proposed [4]. The framework consists of robot design, customer features, and service encounter characteristics. McCartney and McCartney [11] reviewed existing studies on service robot adoption in the tourism and hospitality industry and identified factors that can affect the acceptance of service robots by employees and consumers. Lu et al. [13] conducted a literature review to evaluate the impact of service robots on customers and employees. Their study concluded that current research on service robots is fragmented, is mostly conceptual, and interested in the initial adoption stage. They suggested the inclusion of additional literature streams from information systems, computer science, and engineering.

In light of the limited scope of the existing literature reviews, the main objective of this study is to comprehensively analyze models, methodologies, techniques, and technologies successfully used for service robot development. To achieve this objective, a systematic literature review is conducted to identify impactful papers discussing tools, standards, implementations, practices, and any other technologies for service robots. The following research questions were developed to guide the literature review systematically.

- RQ1: What are the different categories of service robots?
- RQ2: What unique research topics have been addressed in each category?
- RQ3: What are the major technological foundations for service robots?
- RQ4: What are the challenges and opportunities in service robot research?

RQ1 and RQ2 are addressed in Sections 3, 4, 5, and 6. RQ3 is discussed in Section 7 and RQ4 is addressed in Section 8.

2.2. Search Process

Journal/conference articles and book chapters published in the service robot field have been the focus of the search. The keywords, "service robots" "professional robots," "personal robots", and "domestic robots" were used to search for relevant papers. Databases searched include ScienceDirect (Scopus), ACM Digital Library, IEEE Xplore, Web of Science Core Collection, Sage Journals, and Google Scholar.

2.3. Mandatory Inclusion/Exclusion Criteria and Quality Assessment

A set of inclusion and exclusion criteria was established to screen the results of the literature search:

– Only articles written in English were selected;
– Scientific articles published in conferences, workshops, books, and journals were included;
– Articles published before January 1999 were excluded.

Following the inclusion and exclusion criteria, a total of 724 papers published in the service robot field between 1999 and 2021 were selected for preliminary review.

The citations numbers reported in Google Scholar are used as a proxy for the article quality and impact in the field of service robots. For articles published up to 2010, 30 citations were used as the minimum quality threshold. To take into account the potential time lag effect on the article citations, the minimum quality threshold was reduced by 2 citations per year from 2011. For example, 28 citations were used as a minimum quality threshold for 2011 and a minimum quality threshold of 10 citations was used for the 2020 publications. Papers the full-text of which were not accessible from the databases were excluded from the literature review.

2.4. Framework for Systematic Literature Review

Based on the preliminary review of the 724 papers published in the service robot field between 1999 and 2021, research topics and findings were summarized and categorized into seven major themes: (1) professional non-social service robots, (2) professional social service robots, (3) domestic/personal non-social service robots, (4) domestic/personal social service robots, (5) fetching, detection, and navigation, (6) human-robot interaction, and (7) architecture/platform. Figure 1 shows the framework of service robots that consists of the aforementioned seven major themes and their relationships.

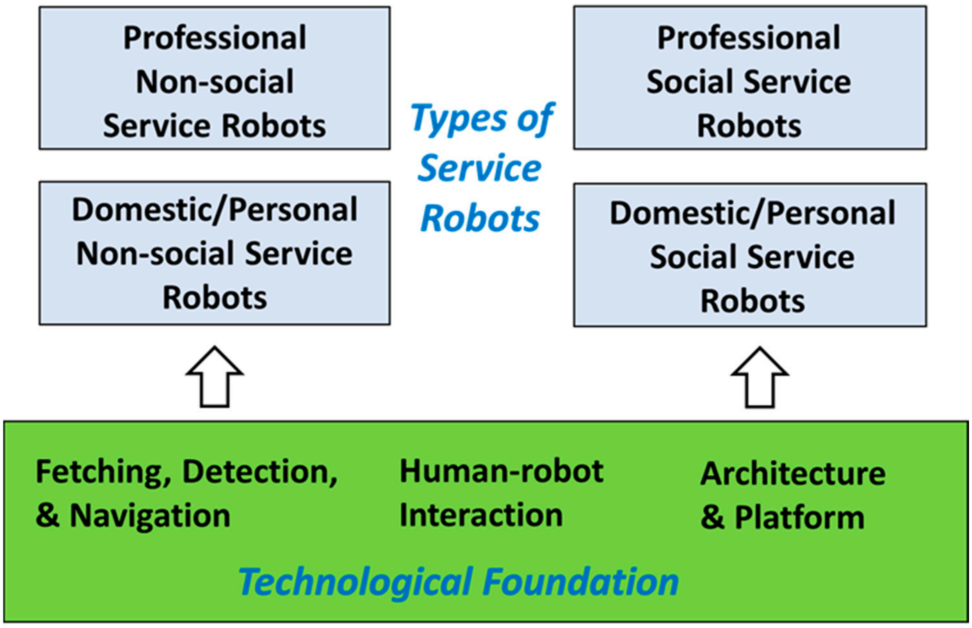

Figure 1. A framework of service robots with seven major themes and their relationships.

For each theme, 10 papers were selected which satisfy the criteria that the study: (1) focuses on technical development and/or human-robot interaction, (2) conducts design, implementation, and experiment/deployment, (3) discusses use cases, and (4) meets the minimum quality citation threshold. A total of 70 papers were selected for the seven themes.

2.5. Data Collection

The data collected from each selected paper include:

- The source (journal/book/conference) and full reference including title and year
- The author(s) and their institution
- Category of the theme
- Research objectives
- Summary of the study including the main research questions and the answers
- Use cases
- Research methods
- Robot development models, methods, and techniques
- Types of experiments and experimental design
- Major findings

To extract and map the key findings of the select paper, a tabular form was developed for each category and used in the systematic literature review.

2.6. Preliminary Data Analysis

Overall, the preliminary data analysis shows that research activities in service robots have been growing over time in a wide spectrum of applications and domains. Table 1 shows 34 journal/book/conference titles from which 70 papers were selected. Table 2 shows the number of papers published by year and journal/book/conference title. The first row represents the publication year from 1999 to 2020. The first column represents the journal/book/conference titles listed in Table 1. Among the journals, Robotics and Autonomous Systems and International Journal of Social Robotics are the top two journal publication outlets with eight papers and six papers, respectively. In the conference category, IEEE/RSJ International Conference and IEEE International Conference on Robotics and Automation are the top two conference publication outlets with 10 papers and six papers, respectively. It is also noted that papers published between 2007 and 2016 were selected more frequently than those from other periods, indicating interesting studies were conducted in that period. The 70 selected papers were classified based on the themes and the results of the literature review are presented in the following sections.

Table 1. The list of journal/book/conference titles.

	Journal/Book/Conference Title
1	*Robot. Auton. Syst.*
2	*IEEE/RSJ International Conference*
3	*IEEE Trans.*
4	*BCS Conf*
5	*Int. J. Adv. Robot. Syst*
6	*Auton. Robots*
7	*Iberian Robotics Conference*
8	*Springer International Publishing*
9	*Ind. Robot Int. J.*
10	*Information*
11	*J. Assoc. Inf. Sci. Technol.*
12	*Intell. Serv. Robot*
13	*ACM/IEEE international conference*
14	*Int. J. Soc. Robot*
15	*Springer Handbook of Robotics*
16	*ACM SIGCHI/SIGART conference*
17	*International Conference on Advanced Robotics (ICAR)*
18	*Engineering*
19	*Int. J. Comput. Intell. Syst*
20	*Expert Syst. Appl*
21	*IEEE International Symposium*
22	*Robotica*
23	*IEEE International Conference on Robotics and Automation*
24	*IEEEASME Trans*
25	*Comput. Electr. Eng*
26	*European Conference on Mobile Robots*
27	*Int. J. Robot. Res*
28	*AAMAS*
29	*IEEE International Workshop*
30	*IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*
31	*Knowl.-Based Syst*
32	*J. Intell. Robot. Syst*
33	*Connect. Sci.*
34	*J. Syst. Softw*

Table 2. Number of articles published by year and journal/book/conference title.

	99	**00**	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Total**
1					1		1			1	1					2	1	1					8
2	1			2		1	1				1	1		2	1								10
3									1					1									2
4											1												1
5							1					1			1								3
6									1														1
7																		1					1
8																		1					1
9									1					1									2
10																						1	1
11																1							1
12										1		1											2
13											1								1			1	3
14												1	1		1	1		1			1		6
15										1													1
16								1															1
17													1										1
18																	1						1
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21									1											1			2
22									1														1
23						1					1		1	1	1		1						6
24																1							1
25																		1		1			2
26																			1				1
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28																				1			1
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34																					1		1
Total	1			2	2	2	5	1	6	4	5	4	3	8	4	5	4	5	2	3	2	2	

Figure 2 shows major subthemes in each type of service robot that will be discussed in detail in the following sections.

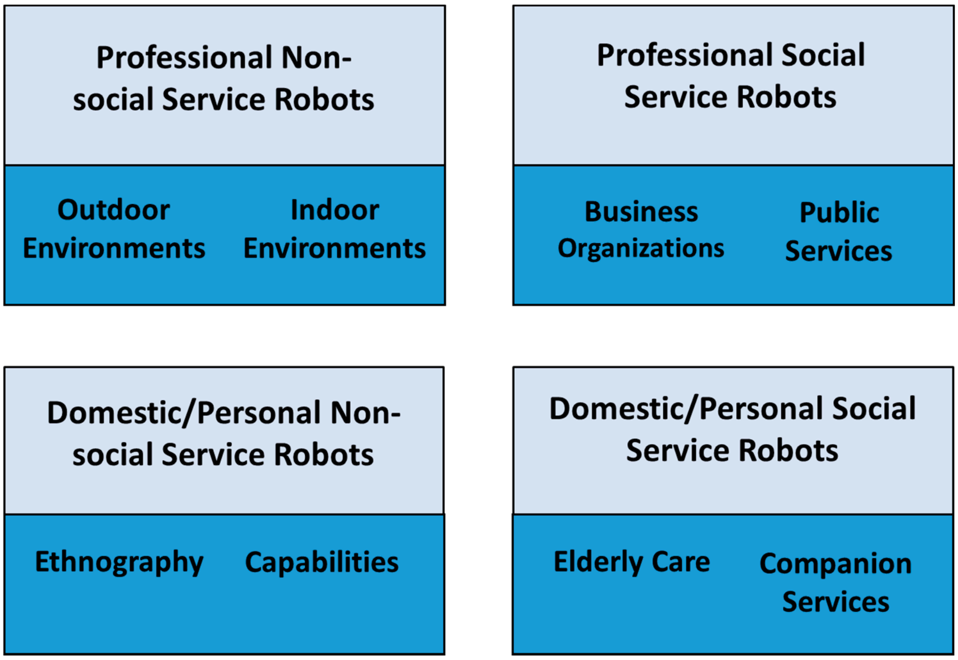

Figure 2. Major sub-themes for each type of service robot.

3. Professional Non-Social Service Robots

Professional non-social service robots provide services for humans or organizations but their services do not necessarily involve social interaction with employees and customers. Examples include inspection robots, cleaning robots, and security service robots. These robots work in indoor environments and outdoor environments and the specific environments drive the development of certain features. Table 3 summarizes the title, purpose, key features, and findings of the ten select papers. In the following, the literature review of the professional non-social service robots is divided into outdoor and indoor application environments.

Table 3. Summary of the paper title, purpose, key features, and findings for professional non-social service robots.

Select Paper	Purpose	Key Features	Findings
Luk et al. [16]	Develop a legged climbing robot for unstructured and rough terrain.	Tactile and ultrasonic sensing; A set of reflexive rules; A fuzzy control method	The developed method allowed for smooth and accurate robot motions and enhanced the walking and climbing activities.
Elkmann et al. [17]	Explore feasibilities for robots to engage in facade cleaning.	A range of motion systems for walking, wheeled, and balloon-based robots	Facade cleaning robot cleaned the vaulted glass hall of the Leipzig Trade Fair in Germany.
Shieh et al. [18]	Develop an intelligent hospital service robot.	Collision-free navigation path planning with nine ultrasonic sensors installed to assess the distances between the service robot and obstacles	The simulation showed that the robot can accomplish navigation control in the hospital environment.
Luo and Lai [19]	Develop an intelligent service robot that can roughly calculate the environmental structure and detect the symbols/signs in the building.	Multisensor fusion techniques; An improved alignment technique	The concept was proved with an information-enriched map.

Andras et al. [20]	Design an indoor service robot locomotion technology.	Platform with mechanical, navigational, and control subsystems	The viability of the indoor locomotion technology was proved.
Ondas et al. [21]	Develop a small service robot performing in teleoperator mode.	Speech interface based on acoustic models; A small-vocabulary language model	The proposed approach performed the best when the background noise is mostly stationary.
Chung et al. [22]	Achieve system integration, multi-functionality, and autonomy under environmental uncertainties.	Modular and reconfigurable hardware components; Navigation system with range sensors; Path planning based on Konolige's gradient method	The public service robot systems accomplished a delivery, a patrol, a guide, and a floor cleaning task.
Zhang et al. [23]	Propose an auto-climbing robot that can clean the spherical surface.	An intelligent control system based on 6 parts, five controller area network (CAN) control nodes, and a remote controller	The experimental results confirmed the robot's ability to clean the spherical surface.
Scholl et al. [24]	Develop a prototype multijoint, autonomous sewer robot.	A distributed hardware architecture with microcontrollers; Sensors to control the joints of the robot; A camera-based system; The robot control system	The robot followed a path with a given speed and adapted the drive segments to the ground.
Baraka et al. [25]	Investigate the use of lights to visualize the robot's state.	Lights as a medium of robot-human communication to reveal the internal state of the robot	The results showed that a small set of visualization designs can be considered valid.

3.1. Professional Non-Social Robots in Outdoor Environments

Several professional non-social robots have been developed to perform crawling and climbing in hazardous work environments. Luk et al. [16] developed an intelligent legged climbing service robot for remote maintenance applications in hazardous environments. Their Robug IIs could walk from the floor to the wall and had the intelligence to search for suitable footholds for gripping in relatively unstructured environments. SCORPIO is a small-size mini-teleoperator mobile service robot for booby-trap disposal [21]. As an auxiliary function, the remote speech interface was developed for a human operator to concentrate on sight and the design and development process of the remote speech interface was discussed.

A variety of facade cleaning robots were developed that are especially suited for the motion for different building types [14]. A facade cleaning robot, SIRIUSc, was used on the vertical and steeply inclined structure surfaces and facades. It was deployed to clean the vaulted glass hall of the Leipzig Trade Fair in Germany. Taking the National Grand Theater of China as the operation target, a robot was developed which autonomously climbs in the up-down direction and cleans outer walls in the right-left direction [23]. A unique movement mechanism was developed to meet dexterity and weight requirements. A prototype of a multijoint autonomous sewer robot was developed along with electric architecture and a controlling mechanism [24]. Both hardware and software components were built on a modular basis to allow for incremental development. Its implementation enabled the robot to follow a path with different speeds.

3.2. Professional Non-Social Robots in Indoor Environments

Many service robots are operated in various indoor environments. For example, an intelligent hospital service robot (IHSR) is an indoor service robot equipped with navigation path planning based on the distribution of people in the hospital [18]. A camera and nine ultrasonic sensors installed were used to estimate the distances between the IHSR and obstacles. An integrated fuzzy controller was proposed as the collision-free navigation control system. For successful navigation, simultaneous localization and mapping (SLAM) techniques were implemented [19]. An intelligent service robot (ISR) detects meaningful symbols or signs and creates information enriched map [19]. A SICK LMS-100 laser range finder and a paired camera were used to create an information enriched map, and patterns of interest (POI) detection and estimation methods were applied to locate the position of POI in the map.

A major challenge in robot movements is to make the robot navigate in any direction [20]. The ACROBOTER platform was developed for a robot to work autonomously in close cooperation with humans and collaborate with other robots in a room environment [20]. The mechanical sub-systems include the grid of anchor points on the ceiling of constructed environments, the climber unit that moves on the grid of anchor points, the swinging unit which is connected onto the climber unit, and the ducted fan system for fine positioning and stabilization of the motion.

Multi-functional PSR (public service robots) systems for indoor services were developed [22]. The PSR robots were designed to conduct a guide, a patrol, a delivery, and a floor cleaning task. Three key elements of the service robots are system integration, multi-functionality, and autonomy under uncertainties. For multi-functionality, modular and reconfigurable hardware components were used. Autonomy under uncertainties was achieved with adaptive localization algorithms and explicit discretization of robot status.

The use of lights was considered to visualize the robot’s state to humans in tasks and environments [25]. The study focused on three situations facing a mobile service robot: (1) waiting for human input, (2) being blocked by a human obstacle, and (3) showing task progress to a user. The results showed that some visualization alternatives can be eliminated. While there was generally a clear preference for one of the visualization alternatives in each scenario, the study suggested that the distribution of preferences can be used to generate probabilistic visualization rather than using a single visualization.

4. Professional Social Service Robots

Professional social service robots provide employees and customers with interactive situation-specific services. Professional social service robots should be prompt to customers’ service needs and sensitive to the customers’ and employees’ satisfaction levels. Professional social service robots such as restaurant and retailer service robots are equipped with some degree of social skills to provide customers with predefined services. Table 4 summarizes the title, purpose, key features, and findings of the ten select papers. In the following, the literature review of the professional social service robots is divided into business organizations and public services.

Table 4. Summary of the paper title, purpose, key features, and findings for professional social service robots.

Select Paper	Purpose	Key Features	Findings
Pinillos et al. [26]	Assess the robot's capabilities as a bellboy in a hotel for guiding the guests and providing hotel/city information and hotel-related services.	Three-stage assessment methodology (data collection, analysis, redesign) with the continuous and automated measurement of metrics regarding navigation and interaction with guests	Following the extensive experimentations, guidelines are derived to integrate social service robots into daily life.

Triebel et al. [27]	Present a socially compliant mobile robot platform developed in the EU-funded project SPENCER.	The platform with the map representation, the task and motion planner, and the laser-based people and group tracker	The robot can engage with a person and guide the person or a group to the goal.
Qing-xiao et al. [28]	Design a restaurant service robot that provides basic services.	Landmarks positioning and localization algorithms, optical character recognition technology, and Radio Frequency Identification(RFID)-based localization algorithm	The restaurant service robot realized real-time self-localization using the algorithms.
Yu et al. [29]	Present segmented positioning and object tracking methods.	Two manipulators with three free degrees, the segmented positioning procedure, and object tracking procedure	The service robot achieved self-localization and grasped the plate on the pantry table.
Chen et al. [30]	Develop an attention-based bidirectional long short-term memory (Att-BiLSTM) model for service robots to classify outpatient categories.	Natural language processing; Long-short term memory deep learning model	The robot system based on Att-BiLSTM showed 96% accuracy.
Lin et al. [31]	Develop a library robot for locating resources in libraries.	Anthropomorphic features; Rapid prototyping; Iterative cycles of design and observation	The robot was effective in helping child patrons in locating resources.
Behan and O'Keeffe [32]	Develop an autonomous robotic aid to help users in a library.	Localization techniques wth image processing integrated with sonar data and odometry; The human-robot interaction system	All interacting users thought the robot was functioning successfully within the given environment.
Gross et al. [33]	Develop a view-based robot self-localization approach.	The omnivision system; probabilistic Monte Carlo localization (MCL)	The view-based localization approach seems to be computationally efficient and robust.
Lee et al. [34]	Present the design of Snackbot, a snack delivery robot, at CMU buildings.	A semi-autonomous semi-humanoid robot	Lessons include developing the robot holistically and as a product and a service, and in a way that evokes social behavior.
Zhang et al. [35]	Investigate the effect of service robot interfaces on perceptions and emotional responses of the elderly.	Design of facial configuration, voice messaging, and interactivity	Anthropomorphic and interactive features of service robots induce positive emotional responses.

4.1. Professional Social Service Robots in Business Organizations

Social service robots need to interact with users in a human-friendly and socially acceptable manner. Social service robots require versatile and robust perception systems and solid interaction strategies [26]. A long-term assessment of a service robot in a hotel environment was conducted with Sacarino, an interactive bellboy service robot in a hotel [26]. Sacarino collected data automatically in a real hotel environment. The acquired data were analyzed to continuously refine the robot's operation. An EU-funded project, SPENCER, was aimed at developing a mobile robot platform that efficiently guides overseas passengers at the Schiphol airport for inner-European connections [27]. The mobile robot platform was a human-size platform whose body serves as an information desk. The platform integrated the map representation, the motion planner, and the people and group tracker.

With the use of artificial landmarks, a mobile robot can estimate its position and direction in the landmark frame [28]. The tables in a restaurant were used as artificial landmarks for fast detection, reliable recognition, and accurate self-localization. The high-precision localization of the mobile robot was made with the use of the RFID-based method around pantry tables. The segmented positioning method was used to provide a robot with accurate coordinates in the different stages [29]. The global vision-based localization method and the RFID-based localization method were used to achieve position accuracy. Omnidirectional imaging was combined with the Monte Carlo localization algorithm to track and localize a mobile robot given a graph-based representation of the service area at a maze-like home store [33]. Experiments showed the accuracy and robustness of the omniview-based self-localization method.

4.2. Professional Social Service Robots in Public Services

A natural language processing system and an attention-based bidirectional long short-term memory (Att-BiLSTM) model were developed for the outpatient text classification system by which users can explain their situation to the service robot and the robot can suggest the clinic they should register with [30]. The proposed system achieved 96% accuracy, better than the 94% accuracy of NB and SVM methods. To design automated resource location services at libraries, collaboration was made between professionals in reader services, ergonomics, information design, and robotics [31].

The needs, preferences, and performances of both the child patrons and the librarians were considered in the assessment and design of the library robot. A service robotic assistant, LUCAS, was developed as a library assistant robot [32]. The landmark features of bookshelves were recognized through the extraction of vertical and horizontal line segments. Using the features, the robot's pose was calculated through an application of the extended Kalman filter (EKF) and the matched environment features.

Researchers at CMU developed Snackbot that would navigate semi-autonomously in campus buildings, delivering snacks to office residents and passersby [34]. The design process of Snackbot, which occurred over 24 months, was documented as a contribution for others in the field of the human-robot interface. The lesson gained is that designing social robots requires a team dedicated to an interdisciplinary holistic design process. Zhang et al. [35] studied the effect of service robots' anthropomorphic features on user perceptions and emotional experiences based on first impressions in a typical patient service task. Their findings indicated that for the elderly, anthropomorphic features of service robots promote perceptions of humanness and positive emotional experiences.

5. Domestic/Personal Non-Social Service Robots

Domestic/personal non-service robots such as vacuuming robots and lawn mowing robots are typically used for non-commercial services. While domestic/personal non-service robots are highly autonomous in the predefined task area, they do not require extensive social interactions with users. Table 5 summarizes the title, purpose, key features, and findings of the 10 selected papers. In the following, the literature review of the domestic/personal non-social service robots is divided into ethnography and capabilities.

Table 5. Summary of the paper title, purpose, key features, and findings for domestic/personal non-social service robots.

Select Paper	Purpose	Key Features	Findings
ung et al. [36]	Develop a domestic robot ecology framework.	The framework with three key attributes: physical and social space, social actors, and intended tasks	Found how people accepted robots as a part of the households through four

			temporal stages: re-adoption, adoption, adaptation, and use/retention.
Fink et al. [37]	Investigate the adoption of domestic robots and their niches.	A 6-month ethnographic study with nine households given a Roomba vacuum cleaning	Only three out of the nine households durably adopted the robot.
Prassler and Kosuge [38]	Survey the technologies in domestic robotics, smart appliances, and smart homes.	An overview of domestic cleaning robots for windows, lawn-mowing, floors, and pools robots	The acceptance of a domestic robot is dependent on not only the engineers' ingenuity but also the customers' needs, expectations, and willingness to pay.
Palleja et al. [39]	Model floor-cleaning coverage performances of domestic random path planning robots.	Performances of three commercial floor-cleaning mobile robots and one research prototype are analyzed.	An algorithm based on random path planning assures complete coverage of a closed area but results in an over-cleaning.
Hendriks et al. [40]	Investigate the personality of a robot vacuum cleaner that users desire.	A semi-structured interview was done with six participants to find out the personality of a robot vacuum cleaner that users desire.	The evaluation showed that users recognized the intended personality of the robot. Once users know the personality of their robot, they can interact appropriately and predict how the robot responds.
Forlizzi & DiSalvo [41]	Present an ethnographic study on the use of the Roomba vacuum.	A four-month ethnographic study with 14 semi-structured interviews and home tours with individuals, couples, and families	The results showed how the technology is introduced is critical, how the use of such technology becomes social, and how homes of the future must adapt to future products.
Vallivaara et al. [42]	Present a Simultaneous Localization and Mapping(SLAM) method based on indoor magnetic field anomalies.	Gaussian Processes and a Rao-Blackwellized Particle Filter	The proposed method can be used to acquire accurate maps for the robot coverage problem and reduce over-cleaning.
Verne [43]	Explore how a garden works and the garden changes with the introduction of a robotic lawn mower.	Autoethnography to evaluate personal experiences and thoughts	On top of its primary tasks, the robot mower reveals much wider consequences. Unwanted changes are important for user acceptance or rejection of robots.
de Graaf et al. [44]	Provide insight into the reasons people refused or abandoned the use of a robot.	70 autonomous robots were placed at people's homes for six months and questionnaires and interviews were conducted to understand reasons for refusal and abandonment of the robot.	Robot designers need to create robots that are enjoyable and easy to use to capture users in the short term, and functionally relevant to keep those users in the longer term.
Vaussard et al. [45]	Evaluate the suitability of domestic robotic vacuum cleaners for	An ethnographic study and an analysis of the influence of key technologies on performance to	The question "can a robot be a drop-in replacement to accomplish domestic tasks?" cannot be answered out of the

	their daily domestic tasks.	understand how well a robot accomplishes its task.	box. The answer mostly depends on how the robot is used.

5.1. Ethnography for Domestic/Personal Non-Social Service Robots

A six-month longitudinal study on the use of Roomba vacuuming robots was conducted with 30 household users who had never owned any kind of robotic appliances [36]. As a way to reflect long-term effects, a structured domestic robot ecology (DRE) framework was developed. They explained with empirical examples that long-term patterns go through four temporal stages of pre-adoption, adoption, adaptation, and use/retention. Another study also conducted a six-month ethnographic study with nine households using the Roomba vacuuming robots [37]. They found that only three out of the nine households durably adopted the robot and discussed their findings.

A desirable personality of vacuuming robots was identified and used to develop a video prototype—a mock-up in the form of a film—of vacuuming robots' behavior [40]. The study investigated how people experience the personality of the vacuuming robots as presented in the video prototype. Fifteen participants were asked to describe their overall impression of the vacuuming robot's behavior. The results indicated that people recognized the intended personality in the robot's behavior and predicted how the robot would respond. Forlizzi and DiSalvo developed a qualitative ethnographic study on the actual use of Roomba vacuuming robots [41]. The study found that a robotic vacuum differs from a traditional vacuum in several ways: the point of entry for the product into the family critically affects the family's social relations; unlike other functionality-oriented products, Roomba is described for its aesthetics and symbolic merit as well as its functionality.

An autoethnography was used to explore in-depth how a garden works and the garden changes when a lawn mowing robot is introduced [43]. The study stated that in addition to carrying out its primary tasks, the lawn mowing robot exhibited consequences at a wider scope by transforming gardening from manual work with soil and plants to electrical coupling and engineering. The study suggested that even for motivated users, there may be a limit to how much work and adaptions to their private space they are willing to carry out. De Graaf et al. [44] conducted a six-month home study with 70 autonomous robots to provide insight into the reasons people refused or abandoned the use of a robot in domestic environments [44]. The main reasons for participants to abandon the use of the robot are that the robot is less enjoyable, less useful, and too intelligent or autonomous.

Vaussard et al. [45] integrated results from a technical study on vacuuming robots with findings from a second ethnographic study conducted at people's homes. Seven samples of robots were tested in a simulated environment to identify the main factors on the performance. In addition, nine households participated in an ethnographic study with a vacuuming robot to understand how people use and integrate the robot in their cleaning tasks. While a vacuuming robot is more energy-efficient than a traditional vacuum cleaner, the study identified two major usage barriers from the human side: a lack of trust in the robot and the unwillingness to adapt and make physical alterations to the home.

5.2. Capabilities of Domestic/Personal Non-Social Service Robots

Prassler and Kosuge [38] surveyed the state-of-the-art domestic cleaning robots, ironing robots, and lawn-mowing robots along with a short discussion on technical challenges inherent in the design of cleaning robots such as absolute positioning, sensor coverage for robust obstacle avoidance, area coverage in unknown dynamic environments, multi-robot coordination, and power supply. They also discussed how domestic service robots can be integrated into smart home environments.

The floor-cleaning coverages of three commercial floor-cleaning mobile robots (RC 3000, Trilobite, and Roomba), and one research prototype (RoboNet) were modeled, measured, and analyzed [39]. Roomba covered the largest amount of the ground area in all cases. An exploratory algorithm based on random path planning enabled complete coverage of a closed area but resulted in over-cleaning by the mobile robots. A SLAM method based on indoor magnetic field anomalies was presented to address a localization problem in mobile robot floor-cleaning tasks [42]. Real-world experiments showed that most modern buildings have magnetic field variation sufficient enough to apply the method to mobile robot floor-cleaning tasks.

6. Domestic/Personal Social Service Robots

Domestic/personal social service robots such as pet robots and companion robots need to interact with humans. With the innovations in machine learning, deep learning, and artificial intelligence, service robots have become more social, intelligent, and adaptive. Table 6 summarizes the title, purpose, key features, and findings of the 10 selected papers. In the following, the literature review of the domestic/personal social service robots is divided into elderly care and companion services.

Table 6. Summary of the paper title, purpose, key features, and findings for domestic/personal social service robots.

Select Paper	Purpose	Key Features	Findings
Jayawardena et al. [46]	Assess users' interaction with an older care robot to determine which human and robot factors predict a successful human-robot interaction.	The robot consists of a tiltable head, rotatable torso, a mobile platform with ultrasonic sensors, and several medical service modules.	53 volunteers from a retirement village gave the robot overall high ratings as well as satisfactory ratings in each service module.
Portugal et al. [47]	Develop an appealing indoor mobile robot and provide effective and advanced user–robot interaction.	A modular robotic architecture allowing easy addition of new components; An innovative and affordable social robotic platform for advanced and useful human-robot interaction	The users suggest that the robot could be more human-like. However, it remains uncertain if the elderly necessarily look for increased animacy in a social robot.
Hendrich et al. [48]	Describe the engineering aspects of the service robot with advanced manipulation capabilities.	Data from multiple sources are integrated into the middleware layer; The configuration planner coordinates the system and the robots.	A field test with 70 elderly users showed that the usability and acceptability scores for the robot and the overall system are positive.
Bien et al. [49]	Present a framework for a human–robot interaction (HRI) module with a range of computational intelligence techniques.	Interaction is considered as input and output of the HRI module and the robotic response is a system output in crisp context, fuzzy context, and uncertain context.	A successful example of human-robot interaction was given for each of the three contexts.
Koay et al. [50]	Develop socially acceptable behavior for a domestic robot in a situation where a user and the robot interact with each other in the proximity of the same physical space.	A live HRI study in a home setting using the human-scaled but non-humanoid Care-O-bot®3.	The way a robot presents itself or is presented by others and to the user significantly affects proxemic preferences as well as the users' ability to process its signals in early interactions.

Park and Cho [51]	Propose a systematic modeling approach for several Bayesian networks.	Bayesian networks to supplement uncertain sensor input; Modular design approach based on domain knowledge	Performance was good in every service test case and the system usability scale test for a subjective evaluation of the reasoning modules is satisfactory.
Bandara et al. [52]	Develop a method to improve the interaction between the user and the robot via bidirectional communication.	Conversation management module (CMM); spatial information processor (ISP); cognitive map creator (CMC)	The robot was able to have interactive conversations with the user.
Bedaf et al. [53]	Explore the areas of tension that a re-enablement coach robot can cause.	Scenario-based focus group sessions with older people, informal care takers, and care professionals in the Netherlands, United Kingdom, and France	Older people-users may prefer autonomy over promotion of independence.
Ferrer et al. [54]	Present a novel robot companion approach based on the social force model (SFM).	A unified navigation framework comprised of a general social interaction model based on the SFM, a pedestrian detector system, and a prediction algorithm to estimate the best-suited destination for a person.	The validation of the model was demonstrated with an extensive set of simulations and real-life experiments in an urban area.
Dautenhahn et al. [55]	Explore people's perceptions and attitudes towards a future domestic robot companion.	The analysis of questionnaire data regarding people's perceptions and attitudes towards a robot before and after human-robot interaction trials	People frequently cited that they would like a future robot to play the role of a servant which is similar to the human 'butler' role.

6.1. Domestic/Personal Social Service Robots for Elderly Care

Jayawardena et al. [46] assessed people's reactions to an interaction with an elderly care robot designed for the elderly in a retirement village to determine which factors predict a successful human–robot interaction (HRI). In this, 53 participants interacted with the robot for approximately 30 minutes in a real-world environment. The participants gave the robot satisfactory ratings as well as high overall ratings in each service module of greeting, blood pressure, blood oxygen saturation, joke, song, hydration reminder, and instructions. Portugal et al. [47] integrated state-of-the-art, standardized, and interoperable robotic technologies and information and communications technology (ICT)-based care and wellness services in an elderly care center and developed a real-world testbed. Results showed the effectiveness of the integrated architecture and the potential of the system to successfully deliver care and wellness services to the elderly.

Hendrich et al. [48] described an ambient assisted living (AAL) architecture of the domestic robot spanning indoor, residential, and outdoor spaces for the elderly with slight mental or physical disabilities and no prior knowledge of robots. A simple user interface and a set of advanced algorithms for navigation, perception, and manipulation were built into the robots. A field test with 70 elderly users showed that the usability and acceptability scores of the robots and the overall system were positive.

Interaction of the service robot was considered as input and output of the HRI module in three contexts: crisp, fuzzy, and uncertain [49]. The study proposed an effective interaction method for each context. A task planning algorithm and its architecture were developed to deal with well-structured tasks autonomously with a simplified set of commands of the user. Human bio-signals were used as input of the HRI module. A probabilistic fuzzy rule-based life-long learning system was used as a solution in uncertain and time-varying situations. Bedaf et al. [53] presented a scenario involving a re-enablement coach robot for focus group sessions with the elderly, informal carers, and care professionals in the Netherlands, United Kingdom, and France [53]. The results showed that the elderly were open to the idea of having a daily assistive robot. The participants were willing to use a robot performing higher-level coordinating tasks. They also expressed high expectations and demands for the capabilities and intelligence of a robot.

6.2. Domestic/Personal Social Service Robots for Companion Services

A live human-robot interaction study was conducted to identify the relationship between user expectations and proxemics preferences in an interaction with a Care-O-bot®3 service robot [50]. To analyze users' interpretation of the robot's intentions, the study used a simple LED light display panel. The results indicated that the participants were comfortable with the robot approaching the closest distance (0.5 m). For the task requiring relatively more coordination, the participants preferred the robot to approach from the front than for the task requiring less coordination.

A probabilistic model with several Bayesian networks was developed to provide users with high-level context-aware robotic services in a home environment [51]. The Bayesian networks were used to handle uncertain input values reliably. The model was designed modularly based on services and functionalities for efficient modeling and reasoning processes. The results showed that the proposed model is useful for measuring the performance of the Bayesian networks in the home environment and participants were satisfied with every service. Bandara et al. [52] proposed a method to enhance interaction between the user and the robot with a conceptual cognitive map that can be updated and improved with the information conveyed.

A scheme for a robot's human-awareness navigation was developed based on the social-forces concept [54]. Multimodal human feedback was used to obtain a set of weighting parameters for the robot companion's behavior and enhance the behavior. The validation of the scheme was demonstrated with a set of simulations and real-life experiments in an urban area. Dautenhahn et al. [55] investigated people's perceptions and attitudes towards a home robot companion. Results of the questionnaires and human–robot interaction trials from 28 adults showed that 40% of the participants were in favor of the home robot companions and most of them appeared to enjoy interacting with the robots. While the participants liked a robot companion to have human-like communication, they did not want the robot to behave and appear in a purely human-like manner.

7. Technological Foundation of Service Robots

The literature review showed numerous technologies have been developed and implemented for service robots. Based on the thematic analysis of the selected papers, the wide range of technologies is broadly categorized into (1) fetching, detection, and navigation, (2) human–robot interaction, and (3) architecture/platform. The three categories of the technologies are summarized in a table format and discussed as follows.

7.1. Fetching, Detection, and Navigation

Table 7 summarizes the title, use case, purpose, techniques, and performance of the ten select papers. In the following, fetching, detection, and navigation technologies are discussed.

Table 7. Summary of the paper title, use case, purpose, techniques, and performance in fetching, detection, and navigation.

Select Paper	Use Case	Purpose	Techniques	Performance
Ekvall et al. [56]	Object detection and mapping	Integrate SLAM and	SLAM; receptive field cooccurrence	The object detection method could

		object detection/recognition methods.	histograms (RFCH); scale-invariant features (SIFT)	successfully detect objects in cluttered scenes.
Althaus et al. [57]	A humanoid system on wheels called Roboviethe engaging in discussion with a group of people and continuing navigation	Present a state diagram that incorporates both locations in the environment and events of an interaction task.	The topological map; A state diagram	The platform's moving patterns were very similar to those of people.
Pyo et al. [58]	A service robot for daily life assistance for the elderly	Develop an informationally structured environment using distributed sensors.	ROS-TMS (robot operating system–town management system) includes distributed sensors, actuators, robots, and databases	Several experiments showed the suitability of the robot in detection and fetch-and-give tasks.
Jung et al. [59]	A marathoner service robot (MSR) that provides a service to a marathoner in training	Present a human detection algorithm and an obstacle avoidance algorithm for the MSR.	A support vector data description (SVDD) method-based feature selection	The MSR performed a human tracking task without collisions.
Nieuwenhuisen et al. [60]	Anthropomorphic robot for a bin picking and part delivery task	Present an integrated system for a mobile bin-picking and part delivery task.	Navigation and manipulation skills; View planning techniques	The lab experiments showed the applicability of the service robot in the task.
Lin et al. [61]	The home service robot, May, in solving the obstacle avoidance problem	Present a particle swarm optimization (PSO) algorithm, named the PSO-IAC algorithm, to solve the obstacle avoidance problem.	PSO algorithm which integrates the constriction factor and adaptive inertia weight	PSO-IAC algorithm took only a few generations to obtain the optimal solution and did not need to re-exploit and re-explore new particles.
Wu et al. [62]	Semantic hybrid map building for a quasi-structured home	Present the Quick Response(QR) code-based artificial label.	Artificial label Identification with QR code; SIFT matching algorithm; Spectral clustering algorithm; Semantic path planning	The spatial semantic hybrid map captured the human point-of-view of the robot environments and achieved function-driven navigation.
Khaliq and Saffiotti [63]	Navigation of a full-scale robotic system in a real apartment	Propose a stigmergic approach to goal-directed navigation.	A grid of read-write RFID tags embedded in the floor; Algorithms for building navigation maps directly into these tags	The proposed navigation system generated reliable navigation for a full-scale domestic service robotic.

Kim and Chung [64]	A guide robot, Jinny, at the National Science Museum of Korea	Propose a formal selection framework of multiple navigation behaviors for a service robot.	Generalized stochastic Petri nets (GSPNs)	The proposed framework helped the robot select an appropriate navigation behavior.
Lopez et al. [65]	Autonomous guided vehicle (AGV) systems	Present an online trajectory planning and optimization approach for cooperative multi-robot navigation.	An elastic-band-based method for obstacle avoidance; Predictive trajectory planner. A cloud-based navigation infrastructure	The proposed approach successfully obtained smooth transitions with two mobile service robots in all path crossing scenarios.

Ekvall et al. [56] addressed a problem related to a scenario in which the autonomous robot should detect and recognize objects as well as estimate their pose using both SLAM and object detection methods to provide a rich map of the environment. For object detection, the image was scanned using a small search window. The experimental results showed that the object detection method could successfully detect objects in cluttered scenes.

Navigation is an essential capability for mobile robots to move around in their environment [57]. A scenario was developed in which mobile robots are joining a group of people as passive listeners. The topological map was used for the robot to make decisions about which navigational subtasks to initiate. A state diagram incorporated both locations in the environment and an interaction task. Experiments showed that the robot was able to reposition itself when the formation changed and the way the robot moved and found its position was judged to be natural by the test subjects.

Pyo et al. [58] presented an informationally structured platform to support an indoor service robot that performs object detection and fetch-and-give tasks. Distributed sensors embedded in the environment were used to integrate various data and a motion planning system was used to design trajectories for moving, gasping, giving, and avoiding obstacles. Jung et al. [59] developed a human detection method and an obstacle avoidance algorithm for a marathoner service robot (MSR) that provides service to a marathoner in training. The study discussed human feature extraction from laser range finder (LRF) data, a support vector data description (SVDD) algorithm, the nearest neighbor (NN) standard filter, and control and tracking algorithms. Marathoner tracking experiments in an outdoor environment showed that the MSR had satisfactory maximum speed and performed a human tracking task stably without collisions.

An anthropomorphic cognitive service robot, Cosero, was developed for bin picking [60]. The mobile bin-picking task consisted of three phases: (1) the cognition phase for exploring the transport box and recognizing the top-most objects, (2) the pick-up phase for grasping a top-most object out of the transport box, and (3) the place phase for placing the object on the processing station. To handle occlusions in the unordered pile of objects in the transport box, Cosero deployed view planning techniques involving sensor positioning and navigation. The study demonstrated the applicability of the robot to the task.

A particle swarm optimization (PSO) algorithm called the PSO-IAC algorithm was developed for the home service robot, May, to reach the goal position with the obstacle avoidance capability [61]. The proposed PSO-IAC algorithm, which integrated the constriction factor and the improved adaptive inertia weight, had a more complex computing process in each iteration than other PSOs. The simulation experiments showed that the PSO-IAC algorithm took only a few generations to obtain the optimal solution.

To improve unstable image processing and provide semantic concepts of objects and rooms in an indoor environment, two-dimensional artificial object labels based on QR code technology were used [62]. To maintain the navigability of the robot, the SIFT matching algorithm and the spectral clustering algorithm were used. The experiments showed that the spatial semantic hybrid map captured the environments, enabled a high-level reasonable service path, and achieved function-driven navigation for the robot. A stigmergic approach to goal-directed navigation was applied for the navigation of a robot in a real apartment where a team of small ePuck robots built navigation maps directly onto an RFID floor [63]. Experiments demonstrated that the stigmergic approach achieved reliable navigation for the robot performing domestic services in a real environment.

Kim and W. Chung [64] proposed a selection framework of multiple navigation behaviors based on Generalized Stochastic Petri Nets (GSPNs) for an autonomous service robot. The framework helps the robot select the most desirable navigation behavior in run time according to environmental conditions and use the results to improve its future operations. Experimental results of tasks by the guide robot, Jinny, showed that the framework helped the robot select an appropriate navigation behavior in a dynamic environment. Lopez et al. [65] addressed the problem of online trajectory optimization and cooperative collision avoidance in an environment where multiple mobile service robots are operating near each other. In path crossing scenarios the predicted trajectories were shared among robots, and in the case of predicted collisions between two robots, a field-based cooperative trajectory optimization was used.

7.2. Human-Robot Interaction

HRI is another technological pillar for successful service robot development. Table 8 summarizes the paper title, use case, purpose, techniques, and performance of the ten select papers. In the following section, widely used HRI technologies are discussed.

Table 8. Summary of the paper title, use case, purpose, techniques, and performance in HRI.

Select Paper	Use Case	Purpose	Techniques	Performance
Halme et al. [66]	WorkPartner working interactively with humans in an outdoor environment	Present the mechatronic structure, the functional subsystems, and motion control principles of the robot.	A mobile hybrid platform; human-machine Interface (HMI)	The HMI is multimedia-based and highly interactive. presence model.
de Jong et al. [67]	Pepper, an interactive humanoid robot	Extend and evaluate Pepper's capability for human-robot social interaction.	State-of-the-art vision system (OpenPose real-time pose detection library and keypoint-based object detection algorithm); Speech recognition system (augmented the existing software with cloud-based speech recognition)	For successful interaction, Pepper should not only sense and understand human input but also be able to verbalize its own experience.
Böhme et al. [68]	A robot as a mobile information kiosk in a home store	Develop a multi-modal scheme for human-robot interaction for a wide range of intelligent service robots.	Vision-based potential user detection method; A biologically inspired model of binaural sound localization; An integrated localization system	The experimental results demonstrated the principal functionality of the corresponding subsystems.

Lee et al. [69]	Service robots in home-based daily activities	Present a human–robot interaction framework that guides a general structure of future home service robots.	Three interaction modules: multimodal, cognitive, and emotional interaction modules	The concept for software integration and the relationships among the three modules were discussed, but no experiments were conducted.
Kwon et al. [70]	Emotion interaction systems for service robots greeting a guest	Develop a framework of emotion interaction for service robots.	The emotion interaction system composed of the emotion recognition, generation, and expression systems.	Even though the multi-modal emotion recognition and expression technologies are still in their early stage, the proposed system is useful for service robot applications.
Droeschel et al. [71]	Person awareness and gesture recognition of a service robot in a laboratory environment	Propose an approach for a domestic service robot that integrates person awareness with pointing and showing gestures.	Laser-range finders; Time-of-Flight camera .	The proposed system achieved higher accuracy than previous studies for a stereo-based system.
Ding et al. [72]	Hand gesture Human-Computer Interactions (HCIs) for disabled people with mobility problems	Design hand gesture HCIs for disabled people with mobility problems.	Mobile service robot platform; Three-dimensional (3D) imaging sensors; Wearable Myo armband device	The results demonstrated the effectiveness of the methods.
Luo and Wu [73]	Hand sign recognition for human-robot interaction	Present a combining method.	Hand skeleton recognizer (HSR); Support vector machines (SVM)	The study demonstrated gesture recognition experimentally with a successful proof of concept.
Bien and Lee [74]	Stewardess robot with the sign language recognition and personalized facial expression recognition, and probabilistic fuzzy rule-based behavior learning	Present the soft-computing toolbox approach for effective hybridization of intelligent techniques for the design of a human-friendly system.	Fuzzy logic-based learning techniques; Soft computing toolbox	Fuzzy logic-based hybrid learning techniques worked for some recognition systems in the HRI process.
Pacchierotti et al. [75]	A robot that operates in hallway settings	Design social patterns of spatial interaction for a robot operating in hallway settings based on the rules of proxemics.	A module for mapping the local environment; A module for people detection and tracking; A module for navigation in narrow spaces; A module for navigation among	The robot with the best behavior was the one with higher speed, larger signaling distance, and larger lateral distances.

	dynamically changing targets	

Halme et al. [66] developed an interactive service robot called WorkPartner (WP) which was wirelessly connected to the user and the Internet through a WLAN [66]. A human-machine interface utilized voice, gestures, and a symbolic representation of the workspace as the main communication method. The symbolic representation is based on the idea that both the robot operator and the robot should interpret the perceived environment through a commonly understood model. The robot recognized gestures with a camera mounted on its head or through a haptic device.

A multi-modality approach was used to increase the robustness of human-robot social interaction [67,68]. State-of-the-art human pose and object detectors were provided to a service robot, Pepper, for a broader range of visual stimuli [67]. For the speech modality, cloud-based speech recognition and built-in speech software were used. Pepper monitored input reliability and sought input from multiple modalities when one modality proves unreliable. Another study also showed that the multimodal integration of vision and sound led to a very reliable people-tracking method [68].

To make a robot better comprehend the intention or the emotional states of a human companion, a general framework of HRI was proposed with three interaction modules: multimodal, cognitive, and emotional interaction [69]. The integration of multiple information obtained from various sensory modalities and coherence maintenance between expressive channels are the core of the multimodal interaction module. The purpose of the cognitive interaction module is the cooperative sharing of tasks with a human user, and the purpose of the emotional interaction module is to maintain a social relationship with a human user. These three modules were integrated into a single system to enhance inter-module interactions. Similarly, Kwon et al. [70] proposed an emotion interaction system composed of emotion recognition, generation, and expression systems. The speech emotion recognition system is a text-independent and speaker-independent recognition system to capture a user's emotion with multi-modality such as touch, voice, and dialogue. The emotion generated by the emotion generation system is expressed by facial expressions, gestures, and the musical sound of the robot.

Droeschel et al. [71] proposed an HRI approach to both awareness of people and perception of pointing and showing gestures for a domestic service robot. Laser range finders and vision were used to detect and keep track of people. Once the robot approaches a person, it perceives pointing and showing gestures with the use of a time-of-flight camera. Experimental results showed that the robot perceived gestures adequately and estimated the pointing direction with higher accuracy than a stereo-based system. Hand gesture recognition was also studied by [72,73]. Four kernel techniques are presented [72]: (1) Myo armband hand gesture recognition, (2) authentication of users using clustering-based support vector machine classifiers, (3) robot vehicle navigation toward the user, and (4) efficient vehicle positioning based on the face-detection information.

Bien and Lee [74] suggested that a soft computing toolbox approach, especially with fuzzy set-based learning (FSL) techniques, could be effective for recognition of human gestures, human bio-signals, and human's physical status and behavior as well as human intention. They showed that a combination of fuzzy logic, fuzzy clustering, and probabilistic reasoning achieves iterative fuzzy clustering with supervision for the construction of a probabilistic fuzzy rule base. The soft computing toolbox approach was applied to two projects: sign language recognition system and personalized facial expression recognition.

Social patterns of spatial interaction were studied for a robot operating in hallway settings [75]. Three parameters (robot speed, signaling distance, and lateral distance for safe passage) were used for the design of proxemic spatial interaction. The robot perceived to have the best behavior was the one with higher speed, larger signaling distance, and larger lateral distances.

7.3. Architecture/Platform

Many architectures/platforms have been developed for collaborative research and simplified cost-effective robot development. Table 9 summarizes the paper title, use case, purpose, techniques, and performance of the 10 selected papers. In the following, widely adopted architectures/platforms are discussed.

Table 9. Summary of the paper title, use case, purpose, techniques, and performance in architecture/platform development.

Select Paper	Use Case	Purpose	Techniques	Performance
Breuer et al. [76]	Johnny Jackanapes, an autonomous service robot for serving guests in a restaurant	Describe the architecture, algorithms, and real-world benchmarks with Johnny Jackanapes.	System architecture consisting of the modular mobile platform, control architecture based on a deliberative layer, software architecture which is a loosely integrated aggregation of dedicated autonomous components, and service robot simulator	The overall system performance was proven at various RoboCup@Home competitions.
Reiser et al. [77]	A compact service robot for serving drinks	Introduce Care-O-bot® 3, a highly integrated and compact service robot with manipulation, navigation, and vision capabilities.	Hardware setup including 28 DOF; Two SICK S300 laser scanners; The control software; Three independent kinematic chains (manipulator, sensor carrier, tray)	While every single component succeeded in over 70% of the cases, the system accomplished the whole process only 6 out of 15 times.
Puigbo et al. [78]	Human size humanoid robot, REEM, acting as a general-purpose service robot	Develop a control architecture for a service robot to generate and execute its plan for goal attainment.	Four main modules connected: an automatic speech recognition (ASR) module, the semantic extractor module for a goal generation, the reasoner module for goal compilation, action selection, and skill activations, and the action nodes module for the execution of the skills	The system ensures that the robot will find a solution, while the optimality is not guaranteed.
Datta et al. [79]	RoboStudio, a visual programming environment (VPE) to program the interactive behavior of personal service robots	Describe the RoboStudio VPE for robot design.	XML-based Robot Behavior Description Language (RBDL); The RoboStudio interface components; RoboStudio architecture based on	The states generated using RoboStudio represented the same application logic as the hand-coded scripts and

			the open-source NetBeans Platform	therefore, confirmed the validity of the XML code generation.
Delgado et al. [80]	Telepresence robot to facilitate human communication across distances	Propose a real-time (RT) control architecture based on Xenomai, an RT embedded Linux, to control a service robot	Architecture to support cross-domain datagram protocol (XDDP) to facilitate data exchange between RT and NRT tasks; Simple APIs that emulate the Xenomai native functions to create RT tasks	The proposed architecture is essential in designing RT control applications for a mobile robot.
Zieliński et al. [81]	Use of two-handed service robot controllers for solving the Rubik's cube puzzle	Develop universal software for the implementation of service robot controllers.	Robot programming framework, MRROC++; QNX real-time operating system	Experiments with diverse tasks showed that MRROC++ is well suited to producing controllers for prototype service robots.
Niemueller et al. [82]	A database for systematic manual fault analysis of the domestic service robot, HERB	Propose a database system that utilizes common robot middleware to record all data produced at run-time.	A generic robot database, MongoDB, implemented in two frameworks, ROS and Fawkes for data recording facilities	The ability to query specific data sets helped to reduce investigation time.
Quigley et al. [83]	Open-source robot operating system (ROS) related to other robot software frameworks	Present an overview of ROS, an open-source robot operating system.	ROS with the support for peer-to-peer, tools-based, multi-lingual; thin, and free and open-source	The open architecture of ROS facilitates the creation of a wide range of tools such as visualization and monitoring, the composition of functionalities, and ROS packages.
Sanfeliu et al. [84]	A community of robots in distributed heterogeneous systems	Define network robot systems (NRS).	Physical embodiment; Autonomous capabilities; Network-based cooperation; Environment sensors and actuators; Human-robot interaction	NRS applications include network robot teams, human-robot networked teams, robots networked with the environment, and geminoid robots.
Berenson et al. [85]	Path planning tasks of a mobile manipulator and a minimally-invasive surgery robot	Propose a framework, called Lightning, for planning paths in high-dimensional spaces.	A planning-from-scratch module; A module that retrieves and repairs paths stored in a path library.	The retrieve-and repair module produced paths faster than the planning-from-scratch module in over 90% of test cases for the

mobile manipulator and 58% of test cases for the minimally-invasive surgery robot.

Breuer et al. [76] described the control architecture, algorithms, and real-world benchmarks used for the development of Johnny Jackanapes which serves as a research and development platform for real-world domestic service robots. Johnny uses the hybrid deliberative layer (HDL) in which a description logic (DL) reasoner is used for the planning. Johnny uses a component-oriented architecture that supports a loosely integrated aggregation of dedicated autonomous components (ACos). Care-O-bot® 3 is a highly integrated and compact service robot equipped with manipulation, navigation, and vision capabilities [77]. Care-O-bot® 3 uses an end-user-oriented design concept and is a representative service robot with high mechatronic integration and a user-oriented design with many interaction possibilities.

SOAR is a general cognitive architecture for selecting the required skill for the current situation and goal without having a predefined list of plans or situations, and is extended to develop a complex general humanoid robot solving complex tasks [78]. The proposed architecture for the general humanoid robot was composed of four main modules interconnected: an automatic speech recognition (ASR) module, the semantic extractor module, the reasoner module, and the action nodes module [78]. The proposed architecture was tested on a humanoid robot, REEM. The results showed the architecture ensured that the robot will find a solution, but limitations still existed in the control algorithms, and speech recognition, and hardware.

Datta et al. [79] presented RoboStudio, a visual programming environment (VPE), to program the interactive behavior of personal service robots. RoboStudio provides a familiar development environment using common design elements present in most integrated development environments. The RoboStudio interface contains various components: UI components palette window, UI component layout editor window, state navigator window, background actions editor window, expected events editor window, and state transition visualization window. The infrastructure is based on the open-source NetBeans Platform which provides many APIs and services.

Delgado et al. [80] proposed a real-time (RT) control architecture integrated with a communication interface of the cross-domain datagram protocol (XDDP). In the proposed real-time control architecture, Xenomai, an RT-embedded Linux, was implemented alongside the standard Linux kernel. Using this architecture, standard device drivers could be used inside RT tasks without the time-consuming development of RT device drivers. They developed simple APIs that emulate the Xenomai native functions to help users re-use or integrate the proposed architecture to more complicated systems.

A multi-robot research-oriented control programming framework, MRROC++, was developed with a hierarchical structure composed of processes to develop single- or multi-robot hierarchical control systems [81]. MRROC++ provides a library of software modules and design patterns for the development of robot control systems. An MRROC++ based control system is implemented as a set of processes: UI—user interface process, MP—master process, ECP—effector control process, EDP—effector driver process, and VSP—virtual sensor process. A two-arm robot for Rubik's cube puzzle-solving was used to validate the MRROC++ based control system.

Niemueller et al. [82] proposed a generic robot database to record any data generated at run-time, providing support for many robot applications. MongoDB was used for database implementation. The implemented database system was run in real-world experiments on the domestic service robot, HERB. The experiments with synthetic benchmarks demonstrated the system's low overhead. Quigley et al. [83] discussed how ROS relates to existing robot software frameworks. ROS was designed as part of the STAIR project at

Stanford University to meet specific challenges encountered when developing large-scale service robots. ROS has been distributed under the BSD license, which allows the development of both non-commercial and commercial projects in a peer-to-peer topology. The open architecture of ROS facilitates the creation of a wide variety of tools.

The technological advances in robotics, computing, and communications led to network robot systems (NRS) [84]. NRS includes robots, autonomous capabilities, environment sensors and actuators, network-based cooperation among the robots, and human-robot interaction. Applications include network robot teams, human-robot networked teams, robots networked with the environment, or geminoid robots. Berenson et al. [85] proposed a framework, called Lightning, for path planning in high-dimensional spaces. Lightning consists of two parallel-run main modules: a planning-from-scratch (PFS) module and a retrieve-repair (RR) module that retrieves and repairs paths stored in a path library. Simulation experiments showed that the RR module produced paths faster than PFS in over 90% of test cases for a mobile manipulator and 58% of test cases for a minimally invasive surgery robot.

8. Challenges and Opportunities of Service Robot Research

Based on the analysis of mainstream research and practices in the field of service robots, this section discusses challenges and opportunities which are somewhat understudied but important for the development of service robots: safety, security, privacy, and ethics.

8.1. Safety

Safety issues were less studied in the service robot community. Service robots equipped with an array of sensors may need to make complex autonomous decisions based on the massive amount of sensor data, and some of the sensor data may contain noise which may confuse robots and trigger unsafe robot actions. To understand the context, robots should be able to reason about when and how they should process sensor data to obtain information relevant to the context. In addition, situations in which service robots interact with humans may pose a risk of serious accidents for humans due to the malfunctioning of robots. For example, collisions between humans and robots, falling robots, and mechanical and electrical malfunction of robots may occur in the course of human-robot interactions. To guard humans against unintended harms caused by robots, human users need to understand what the robot is doing and will do, as well as the rationales behind the actions of the robot [86].

Although research and development of service robots have been going in the last two decades, it was not until February 2014 that the International Organization for Standardization (ISO) presented a technical framework on the safety requirements for personal care robots (ISO 13482:2014) [87]. In addition to various conventional sensors, AI-enabled new sensors may provide promising solutions for occupational safety and health (e.g., collisions) [88]. The safety features of collaborative industrial robots proposed by ISO 10218-1, 2: 2011 and ISO/TS 15066:2016 may also serve as useful guidelines for service robots. The guidelines include safety-rated monitored stop, hand guiding, speed and separation monitoring, and power and force limiting. Researchers and developers should increase their understanding of robot safety issues and various safety standards to develop safety-aware service robots. For safety and effective HRI, it is imperative to consider a multitude of factors influencing the performance of tasks and regulations/standards [89].

8.2. Security

For a wide acceptance of service robots, there should a high degree of trust between service robots and users. Security is one of the major factors in the trust-building between service robots and users. Operating autonomously, robots are prone to a variety of cyberattacks carried out by adversaries. These adversaries insert false information into the robots or even install malicious software to impede the robots' functionalities and extract sensitive information. Cyberattacks on robots often come through ransomware. A large part of IoT networks has adopted lightweight wireless transmissions that are vulnerable to cyberattacks [90]. These attacks could compromise IoT-enabled robot operations by hampering the sensing, actuating, computational, and communication capabilities of the robots or affecting the robots' mobility [91,92].

Security challenges may be alleviated by establishing strong security technologies such as blockchain, intrusion prevention and detection systems, encryptions, and firewalls built into the service robots. Standard web services will allow heterogeneous robots to execute the computationally intense algorithms over the cloud using a mutual authentication and encryption mechanism [93]. Advanced techniques suitable for robot security need to be further developed including user anonymity, failure recovery, attack resilience, access control, and data encryption.

8.3. Privacy

As service robots collect a large amount of data about users, the opaque practices of the collection and processing of the data such as selling data to the third party may have a detrimental effect on the users' acceptance of the service robots. However, there is still a lack of empirical studies on the prevalence, antecedents, and outcomes of privacy concerns about social robots [94]. If service robots are perceived to be useful by a user, the user will be more likely to develop the intention to use, despite potential privacy concerns [94]. Hence, the users need to know how much personal data will be collected and stored for service improvement or personalized services. More studies are needed for the assessment of privacy concerns, their antecedents and outcomes, and tradeoffs between privacy concerns and benefits from the data collection [95].

8.4. Ethics

The prolonged use of socially assistive robots creates potential ethical concerns [96]. It is well known that the quality of the training data is critical for the machine learning of the robot. If the training data are biased, the decisions/actions made by the robot would be biased. Inadequate training of the robot may also lead to unpredictable outcomes. As the deep learning-based language processing model becomes mainstreamed, ethics has drawn much attention from the natural language processing community due to the potential biases built in the language processing model [86].

Emotional deception and emotional attachment are potential ethical concerns in HRI. There needs to be a thorough study on whether emotional deception by a robot is benevolent and ethically acceptable, especially in the robot's interaction with vulnerable users, [96]. Emotional attachment to the robot may harm the mental health of the vulnerable users when the robot has the capabilities to show empathy and compassion towards the users [97]. As socially assistive robots are increasingly used by vulnerable users such as the elderly with cognitive or physical disabilities, it is essential to establish guidelines on ethically safe and acceptable human-robot interactions. Addressing ethical concerns is an integral part of the design process to incorporate appropriate safety mechanisms into service robots.

9. Conclusions

Behind the phenomenal advance of service robots is robotics which is an interdisciplinary field of computer science, computer engineering, ergonomics, artificial intelligence, organizational behaviors, and mechanical engineering [98]. Service robots hold great promise for lowering service costs, speeding up service processes, and serving customers better across many industries [4,99]. The capabilities of service robots are expected to grow rapidly as the scientific communities push technological innovations in relevant fields such as artificial intelligence, hardware, and network technologies. Along with the growth momentum driven by these technological innovations, COVID-19 is accelerating the demand for customer-facing service robots in various businesses such as hotels and healthcare services [10,100]. Organizations and users of service robots need to continuously assess the opportunities and challenges that the service robots present since they are under constant evolution. For example, restaurant owners have gradually adopted catering robots that have a certain degree of social capabilities to interact with the clients and skills to perform tasks for a variety of catering services [101]. Deep learning methods such as convolutional neural networks have shown promising results for object recognition, facial expression recognition, and speech recognition [102].

In light of the need for a comprehensive view of service robots that can guide the future research direction, this study attempted to provide a systematic literature review of technological developments and identify opportunities and challenges in service robots. The systematic literature review resulted in the development of a unifying framework that consists of four broad types of service robot: (1) professional non-social service robots, (2) professional social service robots, (3) domestic/personal non-social service robots, and (4) domestic/personal social service robots and the three major foundational technologies for service robots: (1) fetching, detection, and navigation, (2) human-robot interaction, and (3) architecture/platform. Finally, this study identified and discussed somewhat understudied but important areas that may shape the future research direction of service robots: safety, security, privacy, and ethics.

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References

1. McLeay, F.; Osburg, V.S.; Yoganathan, V.; Patterson, A. Replaced by a Robot: Service Implications in the Age of the Machine. *J. Serv. Res.* **2021**, *24*, 104–121. https://doi.org/10.1177/1094670520933354.
2. Classification of service robots by application areas. Available online: https://ifr.org/img/office/Service_Robots_2016_Chapter_1_2.pdf (accessed on 21 June 2021).
3. Wirtz, J.; Patterson, P.G.; Kunz, W.H.; Gruber, T.; Lu, V.N.; Paluch, S.; Martins, A. Brave new world: Service robots in the frontline. *J. Serv. Manag.* **2018**, *29*, 907–931. https://doi.org/10.1108/JOSM-04-2018-0119.
4. Belanche, D.; Casaló, L.V.; Flavián, C.; Schepers, J. Service robot implementation: A theoretical framework and research agenda. *Serv. Ind. J.* **2020**, *40*, 203–225.
5. Collins, G.R. Improving human–robot interactions in hospitality settings. *Int. Hosp. Rev.* **2020**, *34*, 61–79. https://doi.org/10.1108/IHR-09-2019-0019.
6. Top Trends on the Gartner Hype Cycle for Artificial Intelligence, 2019. Available online: https://www.gartner.com/smarterwithgartner/top-trends-on-the-gartner-hype-cycle-for-artificial-intelligence-2019/ (accessed on 20 June 2021).
7. Decker, M.; Fischer, M.; Ott, I. Service Robotics and Human Labor: A first technology assessment of substitution and cooperation. Robot. *Auton. Syst.* **2017**, *87*, 348–354. https://doi.org/10.1016/j.robot.2016.09.017.
8. Marketsandmarkets Service Robotics Market by Environment, Type (Professional and Personal & Domestic), Component, Application (Logistics, Inspection & Maintenance, Public Relations, Marine, Entertainment, Education, & Personal), and Geography—Global Forecast to 2025, 2019. Available online: https://www.marketsandmarkets.com/Market-Reports/service-robotics-market-681.html (accessed on 20 June 2021).
9. Brookings Institution Brookings Survey Finds 52 Percent Believe Robots will Perform Most Human Activities in 30 Years, 2018. Available online: https://www.brookings.edu/blog/techtank/2018/06/21/brookings-survey-finds-52-percent-believe-robots-will-perform-most-human-activities-in-30-years/ (accessed on 20 June 2021).
10. Kim, S.S.; Kim, J.; Badu-Baiden, F.; Giroux, M.; Choi, Y. Preference for robot service or human service in hotels? Impacts of the COVID-19 pandemic. *Int. J. Hosp. Manag.* **2021**, *93*, 102795. https://doi.org/10.1016/j.ijhm.2020.102795.
11. McCartney, G.; McCartney, A. Rise of the machines: Towards a conceptual service-robot research framework for the hospitality and tourism industry. *Int. J. Contemp. Hosp. Manag.* **2020**, *32*, 3835–3851. https://doi.org/10.1108/IJCHM-05-2020-0450.
12. Kahraman, C.; Deveci, M.; Boltürk, E.; Türk, S. Fuzzy controlled humanoid robots: A literature review. *Robot. Auton. Syst.* **2020**, *134*, 103643. https://doi.org/10.1016/j.robot.2020.103643.
13. Lu, V.N.; Wirtz, J.; Kunz, W.H.; Paluch, S.; Gruber, T.; Martins, A.; Patterson, P.G. Service robots, customers and service employees: What can we learn from the academic literature and where are the gaps? *J. Serv. Theory Pract.* **2020**, *30*, 361–391. https://doi.org/10.1108/JSTP-04-2019-0088.
14. Kitchenham, B.; Brereton, O.P.; Budgen, D.; Turner, M.; Bailey, J.; Linkman, S. Systematic literature reviews in software engineering—A systematic literature review. *Inf. Softw. Technol.* **2009**, *51*, 7–15. https://doi.org/10.1016/j.infsof.2008.09.009.

15. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. https://doi.org/10.1136/bmj.n71.
16. Luk, B.L.; Cooke, D.S.; Galt, S.; Collie, A.A.; Chen, S. Intelligent legged climbing service robot for remote maintenance applications in hazardous environments. *Robot. Auton. Syst.* **2005**, *53*, 142–152. https://doi.org/10.1016/j.robot.2005.06.004.
17. Elkmann, N.; Felsch, T.; Sack, M.; Saenz, J.; Hortig, J. Innovative service robot systems for facade cleaning of difficult-to-access areas. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Lausanne, Switzerland, 30 September–4 October 2002; Volume 1, pp. 756–762. https://doi.org/10.1109/IRDS.2002.1041481.
18. Shieh, M.Y.; Hsieh, J.C.; Cheng, C.P. Design of an intelligent hospital service robot and its applications. In Proceedings of the 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583), The Hague, The Netherlands, 10–13 October 2004; Volume 5, pp. 4377–4382. https://doi.org/10.1109/ICSMC.2004.1401220.
19. Luo, R.C.; Lai, C.C. Enriched Indoor Map Construction Based on Multisensor Fusion Approach for Intelligent Service Robot. *IEEE Trans. Ind. Electron.* **2012**, *59*, 3135–3145. https://doi.org/10.1109/TIE.2011.2141090.
20. Andras, T.; Kovacs, L.; Bolmsjö, G.; Nikoleris, G.; Stepan, G. ACROBOTER: A Ceiling Based Crawling, Hoisting and Swinging Service Robot Platform. 23rd BCS Conference on Human Computer Interaction, 2009. Available online: https://portal.research.lu.se/portal/en/publications/acroboter-a-ceiling-based-crawling-hoisting-and-swinging-service-robot-platform(d298d25b-2b92-4891-9289-61ac7d76b646).html (accessed on 22 June 2021).
21. Ondas, S.; Juhar, J.; Pleva, M.; Cizmar, A.; Holcer, R. Service Robot SCORPIO with Robust Speech Interface. *Int. J. Adv. Robot. Syst.* **2013**, *10*, 3. https://doi.org/10.5772/54934.
22. Chung, W.; Kim, G.; Kim, M. Development of the multi-functional indoor service robot PSR systems. *Auton. Robots* **2007**, *22*, 1–17. https://doi.org/10.1007/s10514-006-9001-z.
23. Zhang, H.; Zhang, J.; Liu, R.; Zong, G. Realization of a Service Robot for Cleaning Spherical Surfaces. *Int. J. Adv. Robot. Syst.* **2005**, *2*, 7. https://doi.org/10.5772/5800.
24. Scholl, K.-U.; Kepplin, V.; Berns, K.; Dillmann, R. An articulated service robot for autonomous sewer inspection tasks. In Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human and Environment Friendly Robots with High Intelligence and Emotional Quotients (Cat. No.99CH36289), Kyongju, Korea, 17–21 October 1999; Volume 2, pp. 1075–1080. https://doi.org/10.1109/IROS.1999.812823.
25. Baraka, K.; Paiva, A.; Veloso, M. Expressive Lights for Revealing Mobile Service Robot State. In *Robot 2015: Second Iberian Robotics Conference*; Springer: Cham, Germany, 2016; pp. 107–119. https://doi.org/10.1007/978-3-319-27146-0_9.
26. Pinillos, R.; Marcos, S.; Feliz, R.; Zalama, E.; Gómez-García-Bermejo, J. Long-term assessment of a service robot in a hotel environment. *Robot. Auton. Syst.* **2016**, *79*, 40–57.
27. Triebel, R.; Arras, K.; Alami, R.; Beyer, L.; Breuers, S.; Chatila, R.; Chetouani, M.; Cremers, D.; Evers, V.; Fiore, M.; et al. SPENCER: A Socially Aware Service Robot for Passenger Guidance and Help in Busy Airports. In *Field and Service Robotics: Results of the 10th International Conference*; Wettergreen, D.S., Barfoot, T.D., Eds.; Springer International Publishing: Cham, Germany, 2016; pp. 607–622. https://doi.org/10.1007/978-3-319-27702-8_40.
28. Qing-xiao, Y.; Can, Y.; Zhuang, F.; Yan-zheng, Z. Research of the Localization of Restaurant Service Robot. *Int. J. Adv. Robot. Syst.* **2010**, *7*, 18. https://doi.org/10.5772/9706.
29. Yu, Q.; Yuan, C.; Fu, Z.; Zhao, Y. An autonomous restaurant service robot with high positioning accuracy. *Ind. Robot Int. J.* **2012**, *39*, 271–281. https://doi.org/10.1108/01439911211217107.
30. Chen, C.-W.; Tseng, S.-P.; Kuan, T.-W.; Wang, J.-F. Outpatient Text Classification Using Attention-Based Bidirectional LSTM for Robot-Assisted Servicing in Hospital. *Information* **2020**, *11*, 106. https://doi.org/10.3390/info11020106.
31. Lin, W.; Yueh, H.-P.; Wu, H.-Y.; Fu, L.-C. Developing a service robot for a children's library: A design-based research approach. *J. Assoc. Inf. Sci. Technol.* **2014**, *65*, 290–301. https://doi.org/10.1002/asi.22975.
32. Behan, J.; O'Keeffe, D.T. The development of an autonomous service robot. Implementation: 'Lucas'—The library assistant robot. *Intell. Serv. Robot.* **2008**, *1*, 73–89. https://doi.org/10.1007/s11370-007-0005-0.
33. Gross, H.-M.; Koenig, A.; Boehme, H.-J.; Schroeter, C. Vision-based Monte Carlo self-localization for a mobile service robot acting as shopping assistant in a home store. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Lausanne, Switzerland, 30 September–4 October 2002; Volume 1, pp. 256–262. https://doi.org/10.1109/IRDS.2002.1041398.
34. Lee, M.K.; Forlizzi, J.; Rybski, P.E.; Crabbe, F.; Chung, W.; Finkle, J.; Glaser, E.; Kiesler, S. The snackbot: Documenting the design of a robot for long-term human-robot interaction. In Proceedings of the 4th ACM/IEEE International Conference on Human Robot Interaction, New York, NY, USA, 9–13 March 2009; pp. 7–14. https://doi.org/10.1145/1514095.1514100.
35. Zhang, T.; Kaber, D.B.; Zhu, B.; Swangnetr, M.; Mosaly, P.; Hodge, L. Service robot feature design effects on user perceptions and emotional responses. *Intell. Serv. Robot.* **2010**, *3*, 73–88. https://doi.org/10.1007/s11370-010-0060-9.
36. Sung, J.; Grinter, R.E.; Christensen, H.I. Domestic Robot Ecology. *Int. J. Soc. Robot.* **2010**, *2*, 417–429. https://doi.org/10.1007/s12369-010-0065-8.
37. Fink, J.; Bauwens, V.; Kaplan, F.; Dillenbourg, P. Living with a Vacuum Cleaning Robot. *Int. J. Soc. Robot.* **2013**, *5*, 389–408. https://doi.org/10.1007/s12369-013-0190-2.
38. Prassler, E.; Kosuge, K. Domestic Robotics. In *Springer Handbook of Robotics*; Siciliano, B., Khatib, O., Eds.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 1253–1281. https://doi.org/10.1007/978-3-540-30301-5_55.

39. Palleja, T.; Tresanchez, M.; Teixido, M.; Palacin, J. Modeling floor-cleaning coverage performances of some domestic mobile robots in a reduced scenario. *Robot. Auton. Syst.* **2010**, *58*, 37–45. https://doi.org/10.1016/j.robot.2009.07.030.
40. Hendriks, B.; Meerbeek, B.; Boess, S.; Pauws, S.; Sonneveld, M. Robot Vacuum Cleaner Personality and Behavior. *Int. J. Soc. Robot.* **2011**, *3*, 187–195. https://doi.org/10.1007/s12369-010-0084-5.
41. Forlizzi, J.; DiSalvo, C. Service robots in the domestic environment: A study of the roomba vacuum in the home. In Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction, New York, NY, USA, 2–3 March 2006; pp. 258–265. https://doi.org/10.1145/1121241.1121286.
42. Vallivaara, I.; Haverinen, J.; Kemppainen, A.; Röning, J. Magnetic field-based SLAM method for solving the localization problem in mobile robot floor-cleaning task. In Proceedings of the 2011 15th International Conference on Advanced Robotics (ICAR), Tallinn, Estonia, 20–23 June 2011; pp. 198–203. https://doi.org/10.1109/ICAR.2011.6088632.
43. Verne, G.B. Adapting to a Robot: Adapting Gardening and the Garden to fit a Robot Lawn Mower. In Proceedings of the Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction, New York, NY, USA, 23–26 March 2020; pp. 34–42. https://doi.org/10.1145/3371382.3380738.
44. de Graaf, M.; Allouch, S.B.; van Dijk, J. Why Do They Refuse to Use My Robot? Reasons for Non-Use Derived from a Long-Term Home Study. In Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, New York, NY, USA, 6–9 March 2017; pp. 224–233. https://doi.org/10.1145/2909824.3020236.
45. Vaussard, F.; Fink, J.; Bauwens, V.; Rétornaz, P.; Hamel, D.; Dillenbourg, P.; Mondada, F. Lessons learned from robotic vacuum cleaners entering the home ecosystem. *Robot. Auton. Syst.* **2014**, *62*, 376–391. https://doi.org/10.1016/j.robot.2013.09.014.
46. Jayawardena, C.; Kuo, I.H.; Unger, U.; Igic, A.; Wong, R.; Watson, C.I.; Stafford, R.Q.; Broadbent, E.; Tiwari, P.; Warren, J.; et al. Deployment of a service robot to help older people. In Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18–22 October 2010; pp. 5990–5995.
47. Portugal, D.; Alvito, P.; Christodoulou, E.; Samaras, G.; Dias, J. A Study on the Deployment of a Service Robot in an Elderly Care Center. *Int. J. Soc. Robot.* **2019**, *11*, 317–341. https://doi.org/10.1007/s12369-018-0492-5.
48. Hendrich, N.; Bistry, H.; Zhang, J. Architecture and Software Design for a Service Robot in an Elderly-Care Scenario. *Engineering* **2015**, *1*, 027–035. https://doi.org/10.15302/J-ENG-2015007.
49. Bien, Z.Z.; Lee, H.-E.; Do, J.-H.; Kim, Y.-H.; Park, K.-H.; Yang, S.-E. Intelligent Interaction For Human-Friendly Service Robot in Smart House Environment. *Int. J. Comput. Intell. Syst.* **2008**, *1*, 77–93. https://doi.org/10.1080/18756891.2008.9727606.
50. Koay, K.L.; Syrdal, D.S.; Ashgari-Oskoei, M.; Walters, M.L.; Dautenhahn, K. Social Roles and Baseline Proxemic Preferences for a Domestic Service Robot. *Int. J. Soc. Robot.* **2014**, *6*, 469–488. https://doi.org/10.1007/s12369-014-0232-4.
51. Park, H.-S.; Cho, S.-B. A modular design of Bayesian networks using expert knowledge: Context-aware home service robot. *Expert Syst. Appl.* **2012**, *39*, 2629–2642. https://doi.org/10.1016/j.eswa.2011.08.118.
52. Bandara, H.M.R.T.; Muthugala, M.A.V.J.; Jayasekara, A.G.B.P.; Chandima, D.P. Cognitive Spatial Representative Map for Interactive Conversational Model of Service Robot. In Proceedings of the 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), Nanjing, China, 27–31 August 2018; pp. 686–691. https://doi.org/10.1109/RO-MAN.2018.8525778.
53. Bedaf, S.; Draper, H.; Gelderblom, G.-J.; Sorell, T.; de Witte, L. Can a Service Robot Which Supports Independent Living of Older People Disobey a Command? The Views of Older People, Informal Carers and Professional Caregivers on the Acceptability of Robots. *Int. J. Soc. Robot.* **2016**, *8*, 409–420. https://doi.org/10.1007/s12369-016-0336-0.
54. Ferrer, G.; Garrell, A.; Sanfeliu, A. Robot companion: A social-force based approach with human awareness-navigation in crowded environments. In Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan, 3–7 November 2013; pp. 1688–1694. https://doi.org/10.1109/IROS.2013.6696576.
55. Dautenhahn, K.; Woods, S.; Kaouri, C.; Walters, M.L.; Koay, K.L.; Werry, I. What is a robot companion—Friend, assistant or butler? In Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, AB, Canada, 2–6 August 2005; pp. 1192–1197. https://doi.org/10.1109/IROS.2005.1545189.
56. Ekvall, S.; Kragic, D.; Jensfelt, P. Object detection and mapping for service robot tasks. *Robotica* **2007**, *25*, 175–187.
57. Althaus, P.; Ishiguro, H.; Kanda, T.; Miyashita, T.; Christensen, H.I. Navigation for human-robot interaction tasks. In Proceedings of the IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA ’04. 2004, New Orleans, LA, USA, 26 April–1 May 2004; Volume 2, pp. 1894–1900. https://doi.org/10.1109/ROBOT.2004.1308100.
58. Pyo, Y.; Nakashima, K.; Kuwahata, S.; Kurazume, R.; Tsuji, T.; Morooka, K.I.; Hasegawa, T. Service robot system with an informationally structured environment. *Robot. Auton. Syst.* **2015**, *74*, 148–165. https://doi.org/10.1016/j.robot.2015.07.010.
59. Jung, E.-J.; Lee, J.H.; Yi, B.-J.; Park, J.; Yuta, S.; Noh, S.-T. Development of a Laser-Range-Finder-Based Human Tracking and Control Algorithm for a Marathoner Service Robot. *IEEEASME Trans. Mechatron.* **2014**, *19*, 1963–1976. https://doi.org/10.1109/TMECH.2013.2294180.
60. Nieuwenhuisen, M.; Droeschel, D.; Holz, D.; Stückler, J.; Berner, A.; Li, J.; Klein, R.; Behnke, S. Mobile bin picking with an anthropomorphic service robot. In Proceedings of the 2013 IEEE International Conference on Robotics and Automation, Karlsruhe, Germany, 6–10 May 2013; pp. 2327–2334. https://doi.org/10.1109/ICRA.2013.6630892.
61. Lin, C.-J.; Li, T.-H.S.; Kuo, P.-H.; Wang, Y.-H. Integrated particle swarm optimization algorithm based obstacle avoidance control design for home service robot. *Comput. Electr. Eng.* **2016**, *56*, 748–762. https://doi.org/10.1016/j.compeleceng.2015.05.019.
62. Wu, H.; Tian, G.; Li, Y.; Zhou, F.; Duan, P. Spatial semantic hybrid map building and application of mobile service robot. *Robot. Auton. Syst.* **2014**, *62*, 923–941. https://doi.org/10.1016/j.robot.2013.01.001.

63. Khaliq, A.A.; Saffiotti, A. Stigmergy at work: Planning and navigation for a service robot on an RFID floor. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, USA, 25–30 May 2015; pp. 1085–1092. https://doi.org/10.1109/ICRA.2015.7139311.
64. Kim, G.; Chung, W. Navigation Behavior Selection Using Generalized Stochastic Petri Nets for a Service Robot. *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* **2007**, *37*, 494–503. https://doi.org/10.1109/TSMCC.2007.897330.
65. Lopez, F.G.; Abbenseth, J.; Henkel, C.; Dörr, S. A predictive online path planning and optimization approach for cooperative mobile service robot navigation in industrial applications. In Proceedings of the 2017 European Conference on Mobile Robots (ECMR), Paris, France, 6–8 September 2017; pp. 1–6. https://doi.org/10.1109/ECMR.2017.8098677.
66. Halme, A.; Leppänen, I.; Suomela, J.; Ylönen, S.; Kettunen, I. WorkPartner: Interactive Human-Like Service Robot for Outdoor Applications. *Int. J. Robot. Res.* **2003**, *22*, 627–640. https://doi.org/10.1177/02783649030227011.
67. de Jong, M.; Zhang, K.; Roth, A.M.; Rhodes, T.; Schmucker, R.; Zhou, C.; Ferreira, S.; Cartucho, J.; Veloso, M. Towards a Robust Interactive and Learning Social Robot. In Proceedings of the 17th International Conference on Autonomous Agents and Multi-Agent Systems, Stockholm Sweden, 10–15 July 2018; p. 9.
68. Böhme, H.-J.; Wilhelm, T.; Key, J.; Schauer, C.; Schröter, C.; Groß, H.M.; Hempel, T. An approach to multi-modal human–machine interaction for intelligent service robots. *Robot. Auton. Syst.* **2003**, *44*, 83–96. https://doi.org/10.1016/S0921-8890(03)00012-5.
69. Lee, K.W.; Kim, H.-R.; Yoon, W.C.; Yoon, Y.-S.; Kwon, D.-S. Designing a human-robot interaction framework for home service robot. In Proceedings of the ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication, Nashville, TN, USA, 13-15 August 2005; pp. 286–293. https://doi.org/10.1109/ROMAN.2005.1513793.
70. Kwon, D.-S.; Kwak, Y.K.; Park, J.C.; Chung, M.J.; Jee, E.S.; Park, K.S.; Kim, H.R.; Kim, Y.M.; Park, J.C.; Kim, E.H.; et al. Emotion Interaction System for a Service Robot. In Proceedings of the ROMAN 2007—The 16th IEEE International Symposium on Robot and Human Interactive Communication, Jeju, Korea, 26–29 August 2007; pp. 351–356. https://doi.org/10.1109/ROMAN.2007.4415108.
71. Droeschel, D.; Stückler, J.; Holz, D.; Behnke, S. Towards joint attention for a domestic service robot—Person awareness and gesture recognition using Time-of-Flight cameras. In Proceedings of the 2011 IEEE International Conference on Robotics and Automation, Shanghai, China, 9–13 May 2011; pp. 1205–1210. https://doi.org/10.1109/ICRA.2011.5980067.
72. Ding, I.-J.; Lin, R.-Z.; Lin, Z.-Y. Service robot system with integration of wearable Myo armband for specialized hand gesture human–computer interfaces for people with disabilities with mobility problems. *Comput. Electr. Eng.* **2018**, *69*, 815–827. https://doi.org/10.1016/j.compeleceng.2018.02.041.
73. Luo, R.C.; Wu, Y.-C. Hand gesture recognition for Human-Robot Interaction for service robot. In Proceedings of the 2012 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI), Hamburg, Germany, 13–15 September 2012; pp. 318–323. https://doi.org/10.1109/MFI.2012.6343059.
74. Bien, Z.Z.; Lee, H.-E. Effective learning system techniques for human-robot interaction in service environment. *Knowl.-Based Syst.* **2007**, *20*, 439–456. https://doi.org/10.1016/j.knosys.2007.01.005.
75. Pacchierotti, E.; Christensen, H.I.; Jensfelt, P. Human-robot embodied interaction in hallway settings: A pilot user study. In Proceedings of the ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication, Nashville, TN, USA 13–15 August 2005; pp. 164–171. https://doi.org/10.1109/ROMAN.2005.1513774.
76. Breuer, T.; Macedo, G. R. G., Hartanto, R., Hochgeschwender, N., Holz, D., Hegger, F.; Jin, Z.; Müller, C.; Paulus, J.; Reckhaus, M.; et al. Johnny: An autonomous service robot for domestic environments. *J. Intell. Robot. Syst.* **2012**, *66*, 245–272.
77. Reiser, U.; Connette, C.; Fischer, J.; Kubacki, J.; Bubeck, A.; Weisshardt, F.; Jacobs, T.; Parlitz, C.; Hägele, M.; Verl, A. Care-O-bot® 3—Creating a product vision for service robot applications by integrating design and technology. In Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, MO, USA, 10–15 October 2009; pp. 1992–1998. https://doi.org/10.1109/IROS.2009.5354526.
78. Puigbo, J.-Y.; Pumarola, A.; Angulo, C.; Tellez, R. Using a cognitive architecture for general purpose service robot control. *Connect. Sci.* **2015**, *27*, 105–117. https://doi.org/10.1080/09540091.2014.968093.
79. Datta, C.; Jayawardena, C.; Kuo, I.H.; MacDonald, B.A. RoboStudio: A visual programming environment for rapid authoring and customization of complex services on a personal service robot. In Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vilamoura-Algarve, Portugal, 7–12 October 2012; pp. 2352–2357. https://doi.org/10.1109/IROS.2012.6386105.
80. Delgado, R.; You, B.-J.; Choi, B.W. Real-time control architecture based on Xenomai using ROS packages for a service robot. *J. Syst. Softw.* **2019**, *151*, 8–19. https://doi.org/10.1016/j.jss.2019.01.052.
81. Zieliński, C.; Szynkiewicz, W.; Winiarski, T.; Staniak, M.; Czajewski, W.; Kornuta, T. Rubik's cube as a benchmark validating MRROC++ as an implementation tool for service robot control systems. *Ind. Robot Int. J.* **2007**, *34*, 368–375. https://doi.org/10.1108/01439910710774377.
82. Niemueller, T.; Lakemeyer, G.; Srinivasa, S.S. A generic robot database and its application in fault analysis and performance evaluation. In Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vilamoura-Algarve, Portugal, 7–12 October 2012; pp. 364–369. https://doi.org/10.1109/IROS.2012.6385940.
83. Quigley, M.; Conley, K.; Gerkey, B.; Faust, J.; Foote, T.; Leibs, J.; Berger, E.; Wheeler, R.; Ng, A. ROS: An open-source Robot Operating System. In Proceedings of the 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, 12–17 May 2009; p. 6.

84. Sanfeliu, A.; Hagita, N.; Saffiotti, A. Network robot systems. *Robot. Auton. Syst.* **2008**, *56*, 793–797. https://doi.org/10.1016/j.robot.2008.06.007.
85. Berenson, D.; Abbeel, P.; Goldberg, K. A robot path planning framework that learns from experience. In Proceedings of the 2012 IEEE International Conference on Robotics and Automation, Saint Paul, MN, USA, 14–18 May 2012, pp. 3671–3678. https://doi.org/10.1109/ICRA.2012.6224742.
86. Zhong, J.; Ling, C.; Cangelosi, A.; Lotfi, A.; Liu, X. On the Gap between Domestic Robotic Applications and Computational Intelligence. *Electronics* **2021**, *10*, 793. https://doi.org/10.3390/electronics10070793.
87. Villaronga, E.F.; Golia, A.J. Robots, standards and the law: Rivalries between private standards and public policymaking for robot governance. Comput. *Law Secur. Rev.* **2019**, *35*, 129–144. https://doi.org/10.1016/j.clsr.2018.12.009.
88. Howard, J. Artificial intelligence: Implications for the future of work. *Am. J. Ind. Med.* **2019**, *62*, 917–926. https://doi.org/10.1002/ajim.23037.
89. Galin, R.; Meshcheryakov, R. Review on Human-Robot Interaction During Collaboration in a Shared Workspace. In *Interactive Collaborative Robotics*; Springer: Cham, Germany, 2019; pp. 63–74. https://doi.org/10.1007/978-3-030-26118-4_7.
90. Tan, W.; Xu, K.; Wang, D. An Anti-Tracking Source-Location Privacy Protection Protocol in WSNs Based on Path Extension. *IEEE Internet Things J.* **2014**, *1*, 461–471. https://doi.org/10.1109/JIOT.2014.2346813.
91. Sharkey, A.; Sharkey, N. Granny and the robots: Ethical issues in robot care for the elderly. *Ethics Inf. Technol.* **2012**, *14*, 27–40. https://doi.org/10.1007/s10676-010-9234-6.
92. Lin, P.; Abney, K.; Bekey, G. Robot ethics: Mapping the issues for a mechanized world. *Artif. Intell.* **2011**, *175*, 942–949. https://doi.org/10.1016/j.artint.2010.11.026.
93. Chavhan, S.; Doriya, R. Secured Map Building using Elliptic Curve Integrated Encryption Scheme and Kerberos for Cloud-based Robots. In Proceedings of the 2020 Fourth International Conference on Computing Methodologies and Communication (ICCMC), Erode, India, 11–13 March 2020; pp. 157–164. https://doi.org/10.1109/ICCMC48092.2020.ICCMC-00032.
94. Lutz, C.; Tamò-Larrieux, A. The Robot Privacy Paradox: Understanding How Privacy Concerns Shape Intentions to Use Social Robots. *Hum. -Mach. Commun. J.* **2020**, *1*, 87–111. https://doi.org/10.30658/hmc.1.6.
95. Lutz, C.; Schöttler, M.; Hoffmann, C.P. The privacy implications of social robots: Scoping review and expert interviews. *Mob. Media Commun.* **2019**, *7*, 412–434. Available online: https://journals.sagepub.com/doi/abs/10.1177/2050157919843961?journalCode=mmca (accessed on 21 September 2021).
96. van Maris, A.; Zook, N.; Caleb-Solly, P.; Studley, M.; Winfield, A.; Dogramadzi, S. Designing Ethical Social Robots—A Longitudinal Field Study With Older Adults. *Front. Robot. AI* **2020**, *7*, 1. https://doi.org/10.3389/frobt.2020.00001.
97. Sullins, J.P. Robots, Love, and Sex: The Ethics of Building a Love Machine. *IEEE Trans. Affect. Comput.* **2012**, *3*, 398–409. https://doi.org/10.1109/T-AFFC.2012.31.
98. Mejia, C.; Kajikawa, Y. Using acknowledgement data to characterize funding organizations by the types of research sponsored: The case of robotics research. *Scientometrics* **2018**, *114*, 883–904. https://doi.org/10.1007/s11192-017-2617-2.
99. Qiu, H.; Li, M.; Shu, B.; Bai, B. Enhancing hospitality experience with service robots: The mediating role of rapport building. *J. Hosp. Mark. Manag.* **2020**, *29*, 247–268. https://doi.org/10.1080/19368623.2019.1645073.
100. Khan, Z.H.; Siddique, A.; Lee, C.W. Robotics Utilization for Healthcare Digitization in Global COVID-19 Management. *Int. J. Environ. Res. Public. Health* **2020**, *17*, 3819. https://doi.org/10.3390/ijerph17113819.
101. Garcia-Haro, J.M.; Oña, E.D.; Hernandez-Vicen, J.; Martinez, S.; Balaguer, C. Service Robots in Catering Applications: A Review and Future Challenges. *Electronics* **2021**, *10*, 47. https://doi.org/10.3390/electronics10010047.
102. Chen, Y.; Zhang, Z.; Zhong, L.; Chen, T.; Chen, J.; Yu, Y. Three-Stream Convolutional Neural Network with Squeeze-and-Excitation Block for Near-Infrared Facial Expression Recognition. *Electronics* **2019**, *8*, 385. https://doi.org/10.3390/electronics8040385.