International Journal of Advanced Robotic Systems

OPEN ACCESS ARTICLE

Overcoming Barriers and Increasing Independence – Service Robots for Elderly and Disabled People

Invited Review Article

Marion Hersh[1]*

1 University of Glasgow, Glasgow, UK
*Corresponding author(s) E-mail: marion.hersh@glasgow.ac.uk

Received 13 June 2014; Accepted 12 September 2014

DOI: 10.5772/59230

Abstract

The paper discusses the potential of assistive service robots to support disabled and elderly people. It shows that they have considerable untapped potential in this area, but also that inappropriate implementations could increase isolation, reduce independence and lead to users feeling as though they are under surveillance. The main body of the paper presents an overview of existing applications and discusses their benefits and potential problems. This is organized by an extension of the common classification into socially and physically assistive robots by the two categories of sensory assistive and mixed assistance robots. Another more detailed classification is also presented. This discussion is introduced by an overview of many of the technological components of smart mobile robots. It is followed by a discussion of user acceptance. The problems of existing models based on either solely positive or solely negative factors are noted and a model containing both types of factors is proposed. The need for continuing research is noted and various proposals are made.

Keywords Assistive, disabled, elderly, user acceptance, mobile robot, robotic wheelchair, socially assistive robot

1. Introduction

Robots have considerable potential to support elderly and disabled people. However, this potential does not seem to have been realized in practice. For instance, only 159 assistive robots for disabled and elderly people were sold worldwide in 2012 (http://www.ifr.org/service-robots/statistics). This is likely to be an underestimate, as a number of the systems in use are non-commercially available prototypes that do not appear in the statistics. However, even taking this into account, it is a very small number compared to the 1.96 million household robots, including vacuum and floor cleaners and lawnmowers, sold in 2012. It is projected that about 6,400 assistive robots will be sold in 2013-2016 and that substantial expansion will take place over the following 20 years. However, it should be noted that assistive robots are generally much higher technology products than household robots (http://www.ifr.org/service-robots/statistics). They are therefore often correspondingly expensive, and this higher cost will affect their use.

Assistive robots are a type of personal service robot. Together with industrial and professional service robots, this is one of the three main categories into which robots have been divided [1]. According to the International

Standards Organization Standard ISO 8373:2012, which specifies the terminology to be used in discussing robots and robotic devices, and combining the definitions of 'robot' and 'service robot': '*A service robot is a robot or actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, that performs useful tasks for humans or equipment excluding industrial automation applications*.' Autonomy in this context means the ability to perform intended tasks based on current state and sensing, without human intervention. The standard notes that whether a robot is classified as an industrial or service robot depends on the application. Unlike industrial robots, service robots only require a 'degree of autonomy', but not full autonomy or fully automatic operation.

Drawing on a definition of assistive technology [2] and the definition of service robots given above, an 'assistive service robot' can be defined as *an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform tasks and services which are used by disabled and/or elderly people to overcome social, infrastructural and other barriers to independence, full participation in society and carrying out activities safely and easily*. Work on assistive robots started in the early 1960s and has intensified over the past 15 years or so, partly due to advances in technology. While a number of useful assistive robots have been developed, many projects have not gone beyond the prototype stage and others have not even produced prototypes.

The main division of assistive robots is into socially assistive robots, which, for instance, act as companions and toys, and physically assistive robots, such as robotic wheelchairs, smart homes and manipulators [3]. However, it should be noted that, while useful, this division is not always clearly defined. For instance, many of the prototype robots designed for elderly people have both physical and social assistance functions. In addition, devices such as robotic guides for blind people do not really provide either social or physical assistance. Therefore, two further categories will be defined: sensory assistive robots and mixed assistance robots.

A further three categories could be defined, but will not be discussed in this paper: robotic organs and limbs, telemedicine and health monitoring and design for all. Robotic limbs and organs e.g. [4], are better classified as rehabilitation robotics rather than assistive service robotics. One of the main distinguishing factors is the difference between external robots which may interface with the user and robots which become part of or are directly attached to the user's body. However, as is frequently the case, the distinction is not totally clear cut. For instance, the Hybrid Assistive Limb suit, which can be rented in Japan, is reported to carry out movements in response to nerve signals, increasing the wearer's strength up to tenfold [5]. Telemedicine and health monitoring robots are again not strictly assistive technologies, though robots which carry out monitoring in addition to other functions will be considered. Examples include the use of robot teddy bears in the Sincere Kourien retirement home in Japan to monitor response times to spoken questions and the time spent carrying out different activities [5]. It should also be noted that the use of robots in this way raises ethical issues related to the right to privacy.

Design for all personal service robots [6] are personal service robots, including the increasingly popular domestic vacuum cleaners and lawnmowers, which have been designed in accordance with design for all (universal design) principles [7]. Design for all involves making products and services, such as robots, accessible and usable by as wide a range of the population as possible, regardless of factors such as age, gender, disability, size, culture and class. It should be considered part of standard good design practice. In the case of robots (and many other products), appropriate design of the human-machine, in this case the human-robot, interface, is particularly important. This is the means by which the user gives instructions to or operates the robot and receives feedback from it. This may require the robot to have a wider range of input and output options than is commonly the case and/or to be compatible with assistive devices.

Other features which could increase the attractiveness of this type of robot for disabled and elderly people include very competitive pricing, easy and intuitive use, and high robustness and reliability [6]. Comments on some of the popular online shopping sites indicate that a number of users leave a robotic vacuum cleaner on to work while they are out, and that many of these robots bump into furniture. Since moving furniture is likely to be more difficult for disabled and elderly people, these robots will also need improved navigation and obstacle avoidance functions to ensure that they do not bump into and knock over or damage furniture or, even worse, the user, who may be less likely to go out while the robot is working. A number of domestic robots are already able to return autonomously to their docking stations. Useful future developments would include automatic emptying of the containers of vacuum cleaners. Well-designed robotic domestic appliances may have certain advantages and be easier to use for many disabled and elderly people than existing appliances. However, it is important that the availability of design for all domestic appliances which can be used by at least some groups of disabled and elderly people is not used to justify a reduction in the funding of personal assistance.

Despite the increasing popularity of domestic robots, robot development has frequently been considered in the context of industry. However, assistive robots differ from industrial robots in a number of ways. In particular, their users are ordinary disabled and/or older people without specialized training, making it particularly important that the interface is easy to use and that the robot is designed to be fully accessible and usable by the intended user groups. In addition, the robots are often required to operate in unstructured, unfamiliar and unprotected environments, such as a house, giving a requirement for sensors to improve their performance, and/or carry out tasks which cannot be pre-programmed. Unlike industrial robots, where users are kept out of the work envelope while the robot is operating, assistive robots generally need to remain close to the user. In addition, users may not be able to react quickly in case of problems, independently move out of the way, press an emergency switch or do so fast enough. This gives rise to the need for additional safety precautions, as well as an even higher level of reliability than for industrial robots. The psychological aspects of robot use and, in particular, acceptance of the robot by the user, are also important and will be discussed further in Section 7. Unlike the case of industrial robots, aesthetics and an attractive appearance are important for assistive robots. The importance of considering user needs has been noted [8].

1.1 Classification of Assistive Service Robots

The types of assistive service robots which have been developed will now be presented using the four-class categorization presented below. This categorization will be used to order the paper, with physically, sensory and socially assistive and mixed assistance robots discussed in Sections 3–6, respectively. This will be preceded by a discussion of design issues in Section 2, followed by consideration of user acceptance in Section 7. Further discussion and conclusions will be presented in Section 8. The assistive robots discussed in the different sections include the following:

3. Physically assistive robots:
    - 3.1. Smart houses with a range of facilities
    - 3.2. Robotic wheelchairs
    - 3.3. Robotic manipulators for reaching and lifting, personal care, eating and drinking
4. Sensory assistive robots
    - 4.1. Mobility devices for blind people
    - 4.2. Shopping assistance robots
5. Socially assistive robots
    - 5.1. Companion and socially assistive robots
    - 5.2. Robots for autistic children
6. Mixed assistance robots
    - 6.1.Robotic assistants for elderly people

Robotic guides in public buildings may also be of interest to younger and non-disabled people. For instance, robotic shopping guides have been trialled in home improvement stores in Germany [9]. A design for all approach could ensure that they have suitable functionality and interfaces to be of use to disabled and elderly people.

While useful, the expansion above of the two commonly-used categories leaves some overlap, with applications which could fit into more than one category. In addition, a more detailed classification may be required for some applications. An examination of assistive technology models e.g. [2, 10], suggests the categories listed below. It should be noted that the categorization has deliberately been left relatively simple and that a wider number of categories or additional options in each category could be used.

1. User:

1.1. Type of user: All users; particular groups of disabled people e.g. hearing impaired, visually impaired, physically disabled, cognitively impaired, on the autistic spectrum.

1.2. Age: child, teen, adult, elderly

1.3. Gender and cultural factors

2. Functionality

2.1. Physical assistance: types of assistance

2.2. Social assistance and interaction: types of assistance

2.3. Sensory assistance: types of assistance

2.4. Reminders and cognitive assistance: types of assistance

2.5.Mixed assistance

3. Context

3.1. Inside: specific building, different types of building

3.2. Outside

3.3. Both inside and outside

4. Robot technology

4.1. Appearance: humanoid, animal-like, similar to a familiar object, machine-like

4.2. Mobility: stationary, wheeled mobility, legged mobility, other types of mobility

4.3.Autonomy: no autonomy, semi-autonomous/ shared control, autonomous

2. Design Issues

A number of design issues and the associated design choices will now be discussed for mobile robots. While not all assistive robots are mobile, the discussion apart from the mobility component is relevant for stationary robots as well. Mobile robots generally have the following main components or characteristics [6]:

Appearance and interaction:

1. Physical structure, including expressive ability: what the robot looks like and its ability to express 'emotions' and respond to the user will affect potential users' responses and the effectiveness of the interaction with the robot.

Mobility and navigation:

2. Mobility system: the robot has a means of moving itself which is appropriate to the intended activities and the environment. The most common means are wheels followed by legs. Other options include suction cups and adhesive pads. The mobility system also includes one or more motors and drivers.

3. Localization, navigation and obstacle avoidance.

4. System of sensors: this should include both proprioceptive sensors to obtain information about the robot's state and exteroceptive sensors to obtain information about the environment. Sensors may include cameras, infrared and ultrasonar sensors and laser range finders with the laser range finder the most accurate.

Processing, autonomy, control and intelligence:

5. Autonomy: some degree of 'independent' decision-making and control. In some cases, such as many intelligent/robotic wheelchairs and other service robots, there is shared control between the user and the robot [11, 12].

6. Human-Robot-Interface (HRI): an interface with the human operator or user is required to enable the user to provide instructions and receive information and feedback. The interface should be designed to be easy and intuitive to use. The type of interface will depend on the types of users and the circumstances. For instance, a speech interface has certain advantages for many users but is not suitable in noisy environments or for deaf users.

7. Processors: this may involve one or more microprocessors, laptops or other devices. The processors can be on board or external. The processors are programmed to carry out the functions situated in many of the other modules.

8. A multi-layer architecture for an intelligent robot control system: this allows different types of behaviours and interactions between the robot and the user at different levels.

9. Artificial intelligence: the ability to respond appropriately to information from the sensors and use it to determine behaviour, including in unfamiliar environments with limited information, time-variation and uncertainty. An intelligent robot should be able to compensate for all these effects (at least to some extent).

It should be noted that good design practice involves consultation with end-users and preferably their involvement in all stages of the design and development process. This is particularly important in the case of assistive robots and other devices for disabled people, who have very specific requirements.

2.1 Physical Structure and Appearance

The appearance of both physically and socially assistive robots is generally very important to users. However, the required functionality, such as transporting the user in the case of a wheelchair, may place considerable constraints on the appearance of physically assistive robots. In the case of socially assistive robots there is generally more flexibility. Possibly for this reason, there has been more discussion in the literature of the appearance of socially assistive and social robots.

There are a number of different classifications. One approach has the main categories [13]: (i) anthropomorphic or having human characteristics (to some extent) e.g. Robota; (ii) zoomorphic or like an animal e.g. the Sony AIBO dog and the Omron NeCeRo cat [14]; (iii) caricatured with simplified or stereotyped features e.g. the small mechanical character CERO on top of a larger mobile robot [15]; and (iv) functional with a design that reflects the function. Another approach which has, for instance, been used in research into the use of robots with autistic people is based on the following five categories of decreasing resemblance to a person [16]: (i) android: looks like a person, but predictable and repeatable behavior e.g. FACE [17]; (ii) Mascot: abstract or cartoonish type of humanoid form e.g. Keepon [18]; (iii) mechanical: humanoid form with visible mechanical parts e.g. Infanoid [18]; (iv) Animal: looks like pet e.g. Pleo [19]; and (v) non-humanoid mobile robot e.g. Labo-1 [20].

Studies e.g. [21, 22], show that robot appearance is important to users, but there does not seem to be a consensus on preferred appearances or even an understanding of what user characteristics and other factors influence the different preferences. A number of studies have been carried out on user attitudes to robots which resemble people, but the results remain inconclusive. For instance, Mori [23] developed a function relating robot acceptance to the robot's similarity to a person. He found an 'uncanny valley' between two peaks in which robots are too similar to people and the differences cause disquiet. A number of studies e.g. [22, 24, 25, 26], have found that potential users preferred a machine-like to a humanoid robot, with older people preferring robots that resemble familiar objects [26]. On the other hand, there are other studies which show that people prefer software agents with human faces [27, 28, 29], robots which have a more human appearance [30] and robots which communicate in more human ways [31], as well as studies which are more positive about small robots with some human features [26]. It has also been found that a robot's physical appearance leads to social expectations and affects people's ability to interact with it [13]. In particular, too human an appearance may lead to unrealistic expectations.

Many social robots, including socially assistive robots, have some ability to express artificial 'emotions' to facilitate interaction and the expression of 'emotions' can also be used to control transitions between different behaviours [13]. The distinction has been made between realism and credibility, and it has been suggested that appearing credible or believable is more important than realism for social robots [32]. Useful abilities for social robots include respecting personal space, recognizing and interpreting the user's emotions, processing and expressing 'emotions' using a voice, facial expressions and body movements and gestures, communicating and giving the impression of being able to take different perspectives [32]. However, autistic people may prefer robots which are not particularly expressive.

2.2 Mobility

The main classification of mobile robots is into mobile platforms and legged robots.

2.2.1 Mobile platforms

Mobile platforms with external sensors have been available for a number of years and can be used in a wide range of applications. The main components of the robot are situated on the platform and include an on-board PC, drives, a power supply, a human-robot interface and devices, such as wheels, to support movement. Various additional devices can be attached to the platform, including arms, grippers and transportation equipment. Communication between the on-board and supervisory PCs is carried out by radio-based networks and WLAN (wireless local area networking). Examples of mobile platforms include wheelchairs, robotic manipulators on mobile bases, and many socially assistive robots. The majority of mobile robots are wheeled, which gives them advantages with regard to stability. The use of mechanum wheels allows them, in principle, to move in any direction using rollers at an angle around the periphery or sometimes centrally mounted on an axle that can be pivoted [33]. In addition, as will be discussed in Section 3.2, wheelchairs have been developed which can go up and down stairs and which can move on rough terrain.

2.2.2 Legged Robots

Legged robots can work in environments which are unsuitable for wheeled robots. However, the design of legged robots is more complex than the design of wheeled robots, since a generally smooth pace is required and the robot needs to remain stable. Where interaction with the user is involved, the robot will need to be able to move at walking pace, adjust its speed to the user's desired pace, not overbalance the user, and move in a way which looks natural. Legged robots can be classified by their number of legs, i.e. (i) one leg (hopping); (ii) two legs (biped); (iii) four legs (multiped); (iv) six legs (hexapod) and (v) more than six legs (snake). From the control engineering perspective, walking on two legs is a complex stability problem. Bipedal robots have high-order, highly coupled, nonlinear dynamics and discrete changes in dynamics. While walking, the robot alternates between a statically stable phase with both feet on the ground and a statically unstable phase with only one foot in contact [34]. The two main approaches to achieving stable and reliable bipedal walking are walking pattern generators and robot controllers [35, 36, 37]. The mechanisms to prevent overbalance include control of the foot landing position and the desired zero-momentum point [38].

Bipedal walking robots, which are the basis of humanoid robots, can be categorized by their walking mechanisms as follows: (i) static walkers with very slow motion and with stability dependent on the projection of the centre of gravity; (ii) dynamic walkers with feet and actuated ankles, and with stability dependent on joint velocities and acceleration, as well as the possibility of static motion if the feet are large enough and the motion is slow; and (iii) purely dynamic walkers without feet and with the projected centre of mass allowed outside the area of the base of the legs.

2.3 Localization, Navigation and Obstacle Avoidance

Autonomous robot navigation in a particular user's environment requires the abilities [39] to develop a detailed map while being pushed around, to robustly self-localize and avoid collisions, to efficiently pass through narrow doorways and gaps in furniture, and over carpets and thresholds, and to autonomously drive to and dock with the charging station. Localization requires the determination of the robot's pose or x-y coordinates and heading direction, generally by finding the best match between the local map of current observations and the global map. A known initial position can be updated from the robot's movement and sensor readings, with least squares or extended Kalman filtering used to improve the estimate [40]. The initial position can be identified (and updated) by the use of cameras to identify naturally occurring landmarks, the creation of artificial landmarks and their detection using radio beacons or machine vision, and the use of an internal map or occupancy grid that moves with the robot [41]. The two main approaches to modelling indoor robot environments are grid-based, with each grid cell assigned a probability representing the belief it is occupied [42, 43], and topological. The latter approach is graphical, with each node corresponding to a distinct place, situation or landmark, and with arcs used to indicate direct paths between nodes [44, 45].

The main component of robot navigation is path planning. A number of different approaches have been used [46], including cell decomposition, road map and potential field. Local path planning generally refers to obstacle avoidance and uses grid maps that divide the space into regular cells or genetic algorithms [47, 48]. Global path planning generally uses topological maps (graphs).

Simultaneous location and mapping (SLAM) algorithms have become popular during the last decade. In SLAM techniques, the navigation system tries to develop a map of an unknown environment (without *a priori* knowledge), or to update a map of a known environment (with *a priori* knowledge from a given map), while at the same time keeping track of the current location [49]. In addition, a number of more qualitative approaches [50] have been developed in which sensory input is used to recognize and distinguish distinct places in the environment [51, 52]. The resulting spatial representation is typically a graphical representation called a 'topological map', in which vertices stand for places or views and edges link connected or adjacent vertices [53].

Mobile robots use some combination of laser range finders, ultra sonar and infrared sensors and (video) cameras to detect obstacles, with some robots having several different sensor systems and others only one (with lasers considered the most accurate but expensive). For instance, the GuideCane [54] has 10 ultra sonars, whereas the museum guide Rhino [55] has 24 ultra sonars, 56 infrared sensors and a laser range finder, and the guidance and physical support device Guido [56] has a laser range finder, an ultra sonar range finder and a camera. The obstacle and collision avoidance algorithms used include (i) the (μ) dynamic window algorithm to 'repel' the robot away from undesirable areas and to 'attract' it towards goal regions [55, 57]; (ii) the (minimal) vector field histogram [58, 59, 60]; (iii) the use of artificial potential fields [61]; (iv) the curvature velocity method [62]; and (v) the use of fuzzy controllers [63].

2.4 Autonomy and Shared Control

By definition, assistive robots aid their users. This may involve a sometimes considerable degree of robot autonomy. However, it is important that robot autonomy does not reduce the user's autonomy and independence, and that the user is able to maintain high-level control over the robot's activities, for instance, to determine the destination when using a robotic wheelchair. Assistance with low-level command functions, such as avoiding obstacles, can be very helpful to some wheelchair users. This leads to the concept of shared control, with the robot able to accept user input throughout the task, work in conjunction with the user and not have more autonomy than the user wants. The division of labour between the user and the robot will depend on the context and their preferences and need for assistance [15]. Autonomous assistive robots will also need to select their goals based on the user's perceived goals and modify them as the user's goals and needs change [64]. There are also issues of the appropriate response in the case of danger and the need for decisions as to when, if at all, the robot can initiate action and/or override the user.

There are a number of different approaches to classifying shared control and the degree of autonomy. Some of them have been derived in a totally different context, but are still relevant to assistive applications. For instance, Huang et al.'s [65, 66] framework for the autonomy levels of unmanned (sic) systems involves the three dimensions of: (i) activity complexity, (ii) environmental complexity and (iii) human independence. The activity complexity dimension includes the robot's situational awareness and knowledge requirements. The human independence dimension includes the percentage split in decision-making between the user and robot, and the percentage of time during which the robot and user respectively make decisions.

Another approach involves 10 different levels of automation in human-computer decision-making [67]. These range from the user deciding on and instructing the computer to carry out a task to the computer deciding on and carrying out a task without human input. The intermediate options involve some degree of shared control. They have been divided into [11] task and response automation systems. In task automation, the user delegates tasks, such as setting waypoints, to the robot to relieve their physical or mental load. In response automation, the robot pre-empts user action and initiates a task in the interests of safety or efficiency, for instance, to prevent a collision. In the first case, the user initiates the automation, whereas in the second case the robot does. In mixed initiative systems, the robot has authority to initiate tasks. However, deciding on the level of autonomy and authority of the robot is a higher-level task which should be carried out by the user. A further division is based on management by exception or consent strategies for terminating automation, with automation terminated by the user in the first case and by the robot in the second case [68]. In mixed authority systems, the robot can terminate behaviours initiated by the user [11]. Another approach, called 'adjustable autonomy', allows the robot to modify its degree of autonomy due to task requirements or the requirements or performance level of the person [69, 70].

2.5 Human-Robot Interaction

The user needs to interact with the robot in order to operate it, and some human-robot interaction may be required even when the robot is totally autonomous [69]. Three categorizations of human-robot interaction based on five important characteristics, roles and levels of interaction respectively will now be presented. However, no attempt has been made to relate them to each other. The important characteristics [71] are the (i) the level and type of autonomy; (ii) the nature of the information exchange; (ii) the team structure; (iii) the adaption, training and learning of the people and robot; and (iv) the type of task.

The different types of interaction or roles [72] are: (i) a supervisor who monitors the robot's behaviour, but does not necessarily directly control it; (ii) an operator who controls the robot either fully or shares control with it; (iii) a mechanic/programmer who attempts to diagnose and resolve robot problems; (iv) a peer or teammate, with the user and robot working together to complete a task and having either separate or shared subtasks and some degree of shared control; and (v) a bystander, who is in the same environment but who does not control the robot. In the case of assistive robots, the peer or teammate, operator and supervisor roles are the most important. It has been suggested that collaborative work with people requires a robot: (i) to be self-reliant at a basic level to ensure safety; (ii) to have sufficient self-awareness or introspection to recognize its limitations so that it can request human help; (iii) to be able to engage in two-way dialogue; and (iv) to be adaptive and to be able to work with both robot novices and expert team members [13, 73]. The five levels of autonomy are: teleoperation, mediated teleoperation, supervisory control, collaborative control and peer-to peer collaboration [71].

Human-robot interaction generally takes place through an interface which allows the user to give the robot instructions and receive feedback from it. The interface can be defined as the program which translates user commands, for instance from a joystick, to high-level robot commands e.g. to move forward. The appropriate design of the user interface is particularly important to enable easy and trouble-free operation. The interface should be easy to use, place low cognitive load on the user, and be accessible to as wide a range of users as possible, either directly or through compatibility with a wide range of assistive devices. However, controlling a six degrees of freedom manipulator with a single switch device or joystick is not straightforward. The interface should also be integrated with any devices the user is already using, such as wheelchairs and remote control units. In addition, it should be configurable by the end-user (or their personal assistant).

As an example, the wide range of approaches used in wheelchair interfaces includes [74, 75, 76, 77, 78] (i) simple voice commands; (ii) gestures, eye blinks or other eye movements; (iii) the detection of eye position using a camera; (iv) determination of the corneal-retineal polorisation potential and its use to calculate saccadic (rapid) eye movements; (v) face direction; (vi) electromyogram signals from the muscle controlling neck movements; (vii) the degree of force on a handle; (viii) sip and puff devices; (ix) brain activity measured by an electroencephalogram; and (x) nodding movements. In the case of head and eye movements, it is important to distinguish between intended commands and other movements, for instance, to look around. One possible approach involves ignoring quick head movements and only responding to slow steady ones [77]. Questionnaires indicate a preference, including from older adults, for speech control of service robots. However, speech recognition software still has limitations, including errors, the need for training and an inability to recognize more than one person's speech in any interaction. The use of high pitched voices in the robot's output should be avoided as many older people have reduced ability to hear high frequencies.

2.6 Architectures for Intelligent Robot Control Systems

There are two main approaches to the design of control architectures for intelligent robotic systems:

1. Horizontal or deliberative architectures, in which sensory data are combined to develop a centralized world representation. This representation is used to generate a plan, which is executed, and then the process is repeated [79, 80].
2. Vertical or reactive architectures, with a decomposition based on the required activities. Each behaviour comprises the perception, planning and task execution capabilities of a particular aspect of robot control. Behaviours can be decomposed into levels of competence and layers can be added incrementally to improve performance [81].

The horizontal deliberative architecture generally has: (i) a functional or behaviour level; (ii) an executive or execution control level; and (iii) planning- or decision-level layers. They are responsible for: (i) action and perception, interaction with the physical world, controlling actuators and collecting sensory data; (ii) controlling and coordinating function execution according to task requirements; and (iii) task planning and supervision of its execution to achieve goals and deal with goal interaction, respectively [79, 80]. Deliberative control architectures generate intelligent behaviour by using computer programs, which plan how to achieve an outcome, whereas reactive ones use a combination of simple closed-loop controllers which interact with the world. They involve purely symbolic planning and have greater predictive capacities, but require full knowledge of the environment. Reactive models are reflexive, have a faster response and are suited to noisy real-world environments.

Behaviour-based architectures include the subsumption architecture [82] and its extensions and modifications, such as the dynamic subsumption architecture [83] and the servo, subsumption, symbolic (SSS) systems architecture [84]. Making the behaviours as fine-grained as possible can avoid inaccessible internal states [85]. Other architectures combine deliberation and reactivity. These include the 3T architecture, which has three interacting software levels [86]. Task-level control is the basis of the executive layer of three-tiered control architectures [86, 87, 88]. Another approach to the design of robot control systems is based on the requirements for miniaturization, leading to distributed processing in the Khepera miniature robot [89].

The ACHRIN architecture [90] consists of elements or modules grouped into three layers: (i) a deliberative layer which maintains an internal world model used to produce plans or sequences of human/robot actions to achieve a goal; (ii) an execution and control layer which sequences and supervises plan execution; and (iii) a functional layer which consists of functional groups of skills which carry out actions, such as manipulation and navigation.

3. Physically Assistive Robots

3.1 Smart Houses

The focus of this section is on the use of smart homes to provide assistance to disabled and elderly people, particularly, though not only, with regard to carrying out physical activities. However, it should be noted that there is also a body of literature on smart homes and telecare and health smart homes e.g. [91, 92], which will not be discussed, and that it is possible to use smart technologies to provide both types of functionality.

Smart home technologies date back to the 1970s home automation technologies. However, other than infrared remote controllers for appliances, these technologies were not adopted to a significant extent, as they were inflexible, of high cost and did not meet users' needs [93]. A smart home involves the interconnection of appliances and other features by sensors, actuators and computational units, and the use of information and computing technology to anticipate and respond to the occupant's needs [94, 95]; or systems equipped with sensors and actuators, which communicate with each other, monitor the occupants and support them in their daily activities [96]. This integration of home systems, including with the assistance of multi-agent systems, allows communication between them through the home computer and the simultaneous control of different systems in operating or pre-programmed modes using speech and single buttons [97]. The application of data mining and machine learning techniques to this data can be used to discover frequent activity patterns and predict events in order to automate interactions with the environment and respond in a context-aware manner. Context awareness can also be used to facilitate adaptation to changing requirements [98].

The smart and context-aware functions can be supported by active or passive radio frequency identification device (RFID) tags which are able to identify people, animals and objects, and which are now inexpensive. The tags comprise semi-conductor chips and an antenna which transmits data to a wireless receiver [99]. Mobile robots with RFID readers can be used to navigate tagged environments and locate and move objects. Advances in technology mean that sensors can now be located in the environment rather than on the robot, reducing its size and weight [99].

Unfortunately, though various solutions have been proposed, RFID tags are an insecure technology and could be used to track people and their activities [100, 101]. The collection of user and house data also raises privacy management and data security issues, with the possibility of unauthorized and even fraudulent uses of the data, including in ways that may threaten the security of the user and/or their property. There are therefore trade-offs between the benefits and the potential loss of privacy. It should be noted that technological support for independent living and working can be provided without the use of smart technology and could include robot manipulators. However, it is only relatively recently that work on smart houses has considered the incorporation of robots in the design, though smart houses themselves can be considered robots. Non-smart systems would have the advantages of reduced cost and be less intrusive than smart ones, since they would not involve extensive monitoring. They have the disadvantages of reduced functionality and probably also reduced robustness, as it may be easier to build fail-safes and redundancy into smart systems, thereby reducing the risks of malfunction.

Initial approaches to smart home design involved a centralized architecture with all appliances connected to the home network and controlled by the home gateway. However, the availability of ubiquitous computing devices has facilitated the use of distributed architectures. Smart homes should comply with open standards to avoid incompatibility between different products. Examples include the Open Services Gateway Initiative (OSGi), which is an open standard service-oriented component model for deploying services in smart homes. Its use in smart homes is generally based on the client-server model, but it risks single point of failure in the home gateway [102]. Other approaches include the use of a peer to peer architecture with multiple OSGi platforms to distribute the working load over the system with service-oriented components augmented by mobile agent technology for system interaction [102], and a generic five-layer context stack with each layer having a different function [98].

While there are some common factors, many disabled people have distinct needs and could receive significantly greater benefits from smart houses than non-disabled people. However, the availability of smart home systems at a reasonable cost to disabled people may depend on their adoption by the non-disabled population. Unfortunately, separate approaches seem to have been taken to the development of smart homes for disabled and non-disabled people, rather than consideration of design for all or even the development of smart homes for disabled and elderly people, which also have features aimed at non-disabled and younger people.

Smart functions or automated systems which can increase independence and quality of life could form part of a wider approach to barrier-free or accessible building design or design for all. However, smart homes can be used both to support elderly and disabled people and to monitor their activities and determine the extent to which they consistently carry out daily-living activities, with the potential threat of removal to an institution if their performance of daily-living activities is considered unsatisfactory. The detection of abnormal patterns can both be useful in health monitoring and used to control the lifestyles of elderly people or result in unwanted interference when an elderly person changes their patterns in order to, for instance, stay out longer or stay up later. There are also trade-offs between possibly intrusive and unwanted monitoring of the user's position, and activities and the provision of smart functions. It is important that smart house occupants do not feel that they are living under surveillance in a goldfish bowl with no privacy or choice and with the smart system controlling their activities, for instance, by switching all the lights off at a particular time. Instead, the smart house needs to be a tool that occupants have control over and which they can use to increase their independence and enhance their personal autonomy and enjoyment of life. Particularly in the case of people with dementia, there may be trade-offs between safety, and privacy and control. However, there are also issues of the elderly person's attitude to risk-taking and the fact that young non-disabled people are frequently allowed to take risks, for instance to engage in dangerous sports, whereas it often seems to be assumed that elderly and disabled people should not be allowed to take risks.

Consultation with disabled people about smart home technology has identified the following majority (but not universal) preferences [103]: (i) lights turning on automatically on their return home, on entry to a room and at night; (ii) access to a garden and items of equipment; (iii) security, including a facility for viewing visitors at the front door before opening it; (iv) automatic closing of curtains and insulating shutters at night; (v) an 'ordinary' external appearance; (vi) a non-open plan layout, but with sufficient space to manoeuvre and carry out activities; (vii) a central, secure, quiet, private location on the ground floor, on level ground and which is self-contained.

The people surveyed were found to have a pragmatic attitude to technology, with a fairly general willingness to use mobility devices, remote controls and security cameras if they were useful, but not wanting this technology to control their lives or make them isolated. A study of different projects has indicated a greater focus on physical and functional health rather than social interaction, possibly because it is more difficult to integrate social interaction technologies [104].

Three examples will now be presented. Details of other projects and implementations can be found in e.g. [105]. The ground floor Edinburgh demonstration flat [106] has not been lived in, though an identical ambient care system is being used by 20 residents elsewhere. It includes a range of technologies intended to improve quality of life, including (i) an induction loop amplifier for hearing impaired people; (ii) a video entryphone system and keyless door lock; (iii) powered door and window opening and closing systems; (iv) infrared shower tap and tap and toilet flush controls; and (v) a pull cord and portable alarm system. Pre-programmed devices include heating controls and audible reminders via the telephone system. Smart devices include (i) pressure pads to identify movements and trigger other appliances, such as lighting; (ii) window sensors which close the windows when the house is empty; (iii) smoke detectors which interact with door and window opening devices; (iv) curtains which automatically open and close at daylight and night fall; and (v) touch-screen interfaces between users and the operating system.

The home network consists of about 55 nodes connected to a 2-wire Siemens European Installation Bus (EIB) and provides the interconnection to all devices. All data transmission occurs on the bus, apart from signals from infrared devices, such as remote controls, which are translated into bus compatible signals. All rooms are pre-wired with bus wiring and actuators for heating control and security have been fitted. Motors are fitted to all windows, other than the bathroom window, and the front and back doors, and can either work automatically or assist the user. The doors can be unlocked and opened using a remote control and can be unlocked manually in case of an emergency. Unfortunately, the door and window opening devices are large, cumbersome and noisy, and many of the components and interfaces have an industrial appearance and are over-engineered for home use.

The Portsmouth Smart Home [103] has the following smart features: (i) manipulation of sliding doors to give changing combinations of open plan and closed rooms; (ii) links between the garden and the main bedroom and/or the living room, and large windows providing contact with the garden; (iii) provision for cabling in ceiling voids and vertical cavities; (iv) 'smart' dados to contain the large number of boxes that would otherwise be required for sensors, motors, sockets, fuses and junctions. These dados could also facilitate retrofitting smart technology in existing houses and could also contain the heating boosters (fan convectors) and give easier access to the wiring circuits; (v) the use of tungsten filament lamps, as a cheap source of lights which can be dimmed easily and for which replacements are easily available; (vi) the use of a single sensor to detect occupant motion, lighting levels, air temperature, humidity and smoke to reduce the visual impact of sensors. Six dwellings are being built, but the additional smart home electronics will only be installed in three of them at the construction stage. To ensure safety all the motorised doors, windows and locks can be operated manually in the case of motor or power failure; the power circuit for the sensors, switches and motorized doors and windows has battery backup and system failure can be notified, if required, to personal assistants, maintenance people and emergency services.

The Intelligent Sweet Home [107, 108] developed at KAIST, Korea, is designed for wheelchair users and involves an intelligent bed, an intelligent wheelchair and a robotic hoist to transfer the user between the wheelchair and the bed. A central control unit integrates all the components, and all systems are connected by a home network which includes both wired and wireless communication modules. There is a multi-modal interface combining voice recognition and gesture recognition using three cameras. The movement of the robotic hoist can be controlled by the user or automatically. The automatic navigation system for the mobile base of the robotic hoist comprises ceiling-mounted active landmarks and a PC camera on the mobile base to detect them. This robot can also be used to handle objects and open doors. A bed-mounted robot can be used to bring objects to the user and cover them with bedding when in bed. A MANUS robotic arm was used in the prototype.

3.2 Robotic Wheelchairs

Significant numbers of people, though only a small percentage of the population, use electrically powered wheelchairs. Powered wheelchairs are generally prescribed for people who do not have sufficient control of or force in their upper limbs to use a manual wheelchair [109]. Wheelchair use involves two types of control: (i) low-level control e.g. obstacle avoidance and keeping the chair centred in a passage; and (ii) high-level control e.g. directing the wheelchair to a desired location.

Users with good joystick skills can manage the two types of control at the same time, whereas this may be more difficult for people using other types of input devices and those with limited joystick control, visual and/or cognitive impairments, and/or who tire easily [110]. The addition of environmental and user status sensors and artificial intelligence can increase the range of users [109]. A robotic wheelchair can assist users by taking over low-level control, such as avoiding obstacles, so that only high-level directional commands, such as forward or stop, are required. A degree of shared control has been shown to help users avoid accidents [111]. An appropriate balance of control is required, with users generally wanting control over high-level command functions, such as the destination, as well as the ability to vary the wheelchair's level of autonomy. Robotic wheelchairs should be fully compatible with a wide range of input devices, as discussed in Section 2.5. They also need to be highly reliable, robust, physically safe for users, and fault tolerant [112].

Smart wheelchairs have been developed since the 1980s [41]. It should be noted that the terms 'smart' and 'robotic wheelchair' are both used in the literature, and that wheelchairs which provide smart functions meet the definition of robots. Currently available robotic wheelchairs and prototypes offer assistance with different combinations of the following functions: (i) obstacle and collision avoidance; (ii) going through narrow openings, including doorways and between pillars, and manoeuvring in tight corners; (iii) route following and landmark-based navigation; (iv) going up and down stairs and slopes; and (v) traversing narrow hallways or passages, by following the walls or staying in the centre of the hallway or passage.

The features which can be used to classify smart wheelchairs include the following [41]: a basic design approach, input methods, types of sensors, control software, operating modes and whether the wheelchair is commercially available. There seem to have been three main approaches to the design of smart (robotic) wheelchairs. Early smart wheelchairs, such as VAHM [113] and Mister Ed [114], were mobile robots with added seats. The majority of current smart wheelchairs, including NavChair [115], OMNI [116], MAID [117, 118] and SENARIO [119], are commercial powered wheelchairs, with significant modifications. The third option, which has only been applied in a few cases, such as SWCS [120], Hephaestus [121], TinMan [122] and Siamo [123], involves a package of software for smart control functions and sensors which has been designed to be compatible with a number of wheelchairs to which it can be added. This has the advantage of enabling users to access smart functions from their existing wheelchair, thereby reducing costs and ensuring appropriate seating with good comfort and support. However, it has the disadvantage of not being fully integrated with the wheelchair, and this prevents the user's input being fed directly to the processor of the wheelchair's motors without requiring reverse engineering [41].

One approach to shared control involves combining the shared control module with a dynamic local obstacle avoidance module in a hierarchical manner. The user indicates their intentions via a joystick, but the signal may be altered by the collaborative controller, obstacle avoidance module or virtual bumper based on a laser scanner and sonar readings, before being passed to the motor control unit to be executed. [111, 124]. Reduced speed can be used to increase safety and make the control movements and the ride smoother [111], but there are arguments for allowing the user to determine the speed (within the limit of what is possible for the particular wheelchair).

One of the most common barriers experienced by wheelchair users is the presence of stairs without a lift. Many vehicles, including vans, trains and many buses, have a high step, making it difficult for wheelchair users to enter the vehicle without a ramp or lifting apparatus. Although a number of stair-climbing wheelchairs have been developed, none of them are well known, widely available or used by more than small numbers of people. Commercially available stair-climbing wheelchairs based on single-section track mechanisms were first developed in Japan in the 1990s, but these were soon replaced by two-stage tracked mechanisms [125]. Robotic devices which support stair climbing by wheelchair users can be divided into the following three groups, with all options having advantages and disadvantages:

1. Wheelchairs which can be used autonomously on stairs (slopes and rough terrain) but which require special provisions for van entry and ascending stairs backwards: (i) a tracked stair climbing wheelchair, which is not well-suited to general use; (ii) a powered dual-cluster stair climber (articulated), which is wider than standard wheelchairs; and (iii) a powered single-cluster (balancing) stair climber, which requires assistance if appropriate handrails are not provided.

2. Wheelchairs which can be used on stairs with the assistance of, generally, one person: (i) a light-weight manual wheelchair with a stair climbing attachment, with special training generally required for the assistant; (ii) a powered single-cluster stair climber, which has excellent overall mobility in most environments.

3. Lifts, which are generally compact but expensive and dedicated to a single set of stairs: (i) a platform stair lift which carries the wheelchair directly but requires wide stairs; (ii) a stair chair lift, which can be used on narrow stairs but requires a transfer mechanism.

Although a number of prototypes have been developed, only a very small number of robotic wheelchairs are commercially available. One of these few and one of the earliest to be developed is the Call Centre's Smart Wheelchair [126]. It was developed by CALL and the Bioengineering Centre, Edinburgh, in 1987 to investigate the benefits and applications of augmentative control in providing disabled children, who were unable to control a standard powered wheelchair, access to independent mobility. It is sold by Smile Rehab Ltd and meets European Commission specifications. It is based on the following design principles: (i) a division of the different functions into 'tools', each of which performs a single easy-to-understand function; (ii) the ability to mix the functions fairly freely; and (iii) mode-free operation, so that any control included in the system can be used at any time.

It uses a commercially available chassis (see Figure 1) and controller (originally an Everest and Jennings Elite and later a Newton Products standard chassis) with the smart controller electronics connected in place of the standard joystick. Either the standard seat or an individually-tailored one can be used. The computer-based controller and sensors assist the user in the following three ways: (i) providing some safeguards for users who cannot control the wheelchair completely independently; (ii) aiding the user by taking over some of the responsibility for steering and object avoidance; and (iii) integration with communication aids and computers to allow the same controller to be used for the wheelchair and another assistive device, and use of a more powerful computer than the internal one to control the wheelchair. The balance of user and system control is determined by the user and can range from complete user control to the wheelchair deciding where to go and controlling steering and stopping, with the user merely initiating movement.

The design is intended to make it easy for non-technical people to connect and try out different types of tools. The chair can be driven by any switch with a jack plug on the end, including those operated by hand, head, finger, foot, elbow, tongue, breathing in and out (sip and puff), touch and sound. The smart wheelchair's sensors and systems, including bumpers and a line follower, do not operate when the chair is driven with the joystick. The control scheme is intended to allow accurate starting and stopping, avoid activation of the switch by accident, give an easy-to-understand link between the switch and the result, be accessible (including when the wheelchair or user is moving), and allow easy extension to the use of several switches or a scanning selector. There are three types of response to a switch: (i) momentary control in which the wheelchair moves when the switch is pressed and stops when it is released; (ii) timed control in which the chair travels for a certain (short) time and then stops; and (iii) latched control, which is rarely used, but which is useful for people who can activate a switch but not hold it.

A laptop or communication aid can be connected to the chair by an RS232 socket. Commands from the computer or communication aid can be used to move the chair in eight different directions and stop it. Bump tools are used to deal with impacts, allowing the user to concentrate on moving and stopping. Sensors at the front, back and side of the chair sense the location of an obstacle. When an impact occurs, the rubber tube bumpers are squashed and the air inside operates the pressure switch. The line-following options allow the chair to follow a tape track on the ground, with the possibility of choosing the direction at a junction under the line following with a junction option. An observer speech tool can be used to give the user feedback on what is happening so as to help them learn the system. This tool, as well as some of the specific messages, can be turned on or off.

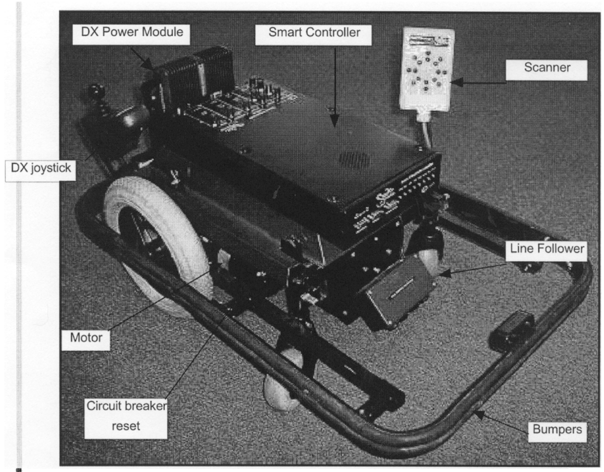

Figure 1. Smart wheelchair chassis with the footplates removed

A number of other robotic wheelchairs will now be discussed, very briefly. Most of them are designed for indoor use only, thereby reducing their usefulness. One exception is the Wheelesley robotic wheelchair [127], based on the earlier Wheeley, and which can be used both indoors and outdoors. It has shared control with the user, can autonomously switch between two navigation modes, and can carry out path-following and obstacle avoidance. It is compatible with the EagleEyes control system based on electro-oculographic potential. The iBot mobility system [128] (see Figure 2), which is no longer in production, was multi-functional, including stair-climbing. It was available on prescription and required user-training. Its main functions were: (i) elevating the user to have eye-level conversations or reach shelves; (ii) stair climbing and descending, both with and without assistance; (iii) climbing curves and travelling on uneven terrain; (iv) remote control to allow the chair to be driven into a vehicle; and (v) standard power chair operation.

Figure 2. iBot 3000

The Hephaestus Smart Wheelchair System [121] and Tao 1 and 2 [129] are examples of robotic navigation modules including sensors which can be interfaced with standard wheelchairs. The Hephaestus is intended to have similar behaviour to the NavChair (see below), with hardware and software designed to facilitate commercialization. The Tao design is based on the five functions of: (i) basic collision avoidance using an on-board charge-coupled device (CCD) cameras and active infrared sensors and speed reduction, followed by stopping or turning away from an obstacle; (ii) autonomous movement through a narrow corridor parallel to the walls; (iii) entry through a narrow doorway; (iv) manoeuvring in a tight corner; and (v) landmark-based navigation using two CCD cameras to detect available free space and identify landmarks, as well as an on-board topological map. Only the first two functions were implemented in the first prototype.

MAID (mobility aid for elderly and disabled people) [117, 118] has a laser rangefinder and a modular sonar system on a commercial electric wheelchair of the Sprint type. (Semi-)autonomous navigation modes support manoeuvring in narrow, cluttered and wide, rapidly changing, crowded areas. RobChair [130] is steered by voice commands assisted by fuzzy logic. It has infrared sensors, sonars and a front bumper. There are five spoken guidance commands: forward, right, left, turnleft (30°) and turnright (30°). The NavChair [115] uses a ring of sonar sensors mounted on the wheelchair tray to navigate indoor office environments. It can select an appropriate operating mode (general obstacle avoidance, door passage and automatic wall-following) automatically, based on the environment or the environment and location. It can be driven using a joystick or voice commands. There are also wheelchairs which have been designed to work together with or otherwise react to a personal assistant. One of them is able to work together with an assistant and follow and respond to their activities using an omni-directional camera and four laser range finders [131, 132]. Another is able to follow a moving target such as a person walking in front, find a trajectory in free space and move in a user-specified direction using sonars and a panoramic camera on a commercially available wheelchair chassis [133].

The Friend robotic system [134] comprises an electric wheelchair equipped with the robotic arm MANUS (see section 3.3) with both devices controlled by a computer mounted in a rigid box behind the wheelchair. A combination of speech commands from the user and semi-autonomous control of the robotic arm supported by data from a camera mounted on top of the gripper is used.

3.3 Robotic Manipulators

Appropriately designed robotic manipulators can increase the independence and quality of life of people with motor impairments. In particular, they can support people with limited hand and arm movements, including those with high-level spinal injuries or tremors. However, it is important that the availability of these devices is not used to reduce the availability of personal assistance, as contact with personal assistants is important to many disabled people [3]. The earliest devices were large, complex and not very attractive, whereas subsequent developments have resulted in smaller, cheaper and more attractive devices. While safety has improved considerably, avoiding risk to users is still a very important consideration.

A number of surveys have identified that disabled people in this group would like assistive devices for carrying out the following activities [135, 136]: (i) eating and drinking; (ii) personal care, including washing, shaving, applying cosmetics or scratching an itch; (iii) handling papers, books, CDs and videos; (iv) mobility and access, such as opening room and cupboard doors, and operating light switches and lift buttons; and (v) general reaching and moving tasks, including reaching up to get an item off a shelf or from a cupboard, and reaching down to pick up an item from the floor, and moving items.

Robot manipulators have been categorized as follows [137, 138, 139]: (i) workstation or desk-based systems in fixed position, including MUSIIC [140], Raid [141] and ProVar [142]; (ii) wheelchair-mounted manipulators, which include MANUS [137] and Raptor [143]; (iii) mobile robot systems, including ARPH [144]. All the categories can be further divided into (i) multi-task and (ii) single-task robotic manipulators, though most of the single-task manipulators are stationary.

All the different types of devices have their applications, as well as advantages and disadvantages. Fixed workstations have the advantages of reduced complexity and price, using standard robots and pre-programmed motions to speed up task execution, but the disadvantage of only being able to access a limited volume of space [139], though the use of longer robotic arms can increase this volume. These robots are best suited to workplaces where speed is important and only a relatively small number of different tasks are carried out. They are likely to be more useful for work-related workstation- or desk-based activities than household activities, which generally use different rooms. The control system has information about the objects, such as books, computers and cups, in the immediate environment of the manipulator, and the user can use pre-programmed functions to pick up and move objects. The robot can also operate in partially unstructured environments.

Wheelchair-mounted systems have the considerable advantages of being mobile and always being with the user, and wheelchair-mounted multi-function devices are the most flexible. However, restrictions on manipulator size result from the requirement of not significantly increasing the wheelchair width in order to allow it to go through doors. The appropriate length for the arm depends on what the user wants to reach, but can generally be shorter than for a fixed station [139].

End-users generally want to be able to control objects in an unstructured world e.g. a cup in an arbitrary position on a table as well as objects such as doors in predefined positions. This is a difficult technical problem. The following two approaches have been used: (i) the end-user identifying objects and guiding the manipulator to them, and (ii) using sensors to obtain information, sensor fusion techniques to extract data and special control algorithms to manipulate the identified objects. Systems in the second category are fairly complex and expensive.

Autonomously mobile systems have some of the advantages of wheelchair-mounted systems and can also be sent to areas the user cannot reach, for instance when in bed. However, they require greater on-board intelligence and autonomy [139]. They include relatively low-cost trolley-mounted systems, which require another person to move the trolley-based system between rooms. Feedback from users indicates that they want greater functionality and a remote-controlled powered system or for the robot to be mounted on the wheelchair.

Important factors to take account of in the design include aesthetics and the attractiveness of the device, reliability and safety, steering and wheelchair usability [135, 145]. The device's appearance and attractiveness are important both because the user will generally spend a considerable amount of time with the device and because it may affect the way other people react to and treat them. In particular, attaching a manipulator to a wheelchair can have a significant visual impact. The user should be the centre of focus, rather than being hidden behind a lot of gadgets, and the manipulator should be attractive, as unobtrusive as possible, and aesthetically integrated with the wheelchair in terms of shape, style and colour. Very high reliability is essential, since users will frequently be dependent on the manipulator and any malfunctions could have a serious negative impact on them. Reliability should include not compromising the control, usability, steering or stability of the wheelchair, for instance as a result of the size, weight and positioning of the robotic arm. In addition, vibration when the manipulator makes contact with an object should be minimized. The arm should also not negatively affect seat adjustment, pressure relief and transfer to and from the wheelchair. It should also have low power consumption and be able to reach floor level and head height. The barriers to the acceptance of robotic manipulators include concerns about size, insufficient functions, poor appearance, taking too long to carry out activities and fears of becoming isolated and a reduction in communication [145].

Single-task robots are designed to carry out a particular task, such as eating or washing. They are very useful but cannot be operated in an unstructured environment. They include a number of commercially available robotic feeding devices which have been in use for a number of years. They are generally relatively inexpensive and, in some countries, the cost can be covered by the medical or social security system. Eating devices enable people with high-level spinal injuries to feed themselves [3], though the food needs to be set up on the system. Robotic systems may have advantages with regard to non-robotic systems in terms of size, appearance and options for user control [3]. The Mealtime Partner and Neater Eater are both available in North America and Europe, and use a rotating food compartment and plate, respectively [3]. The Neater Eater can be operated by a head control device. It has a modular structure which allows it to be tailored to individual requirements. It includes an arm mounted on a choice of baseboards; fold-away clamps for fixing to a table; high-sided ceramic or plastic turntable plates with pegs designed to fit into the baseboard; and plastic or metal cutlery fitted into a holder that clips to the Neater Eater arm. The SECOM MySpoon system [146] used in Japan allows the user to select the control mode from fine directional control, compartmental selection mode and automatic mode. It is small, designed to be incapable of accidentally striking the user's head, and relatively quick to use.

MANUS (or the assistive robotic manipulator – ARM) [137, 139] is a commercially available wheelchair-mounted general purpose manipulator, which has been sold commercially since 1990 and is used by over 100 people, particularly in the Netherlands and France. It allows users to carry out daily living and work tasks at home, work and outdoors. The following specifications were identified before the start of development: (i) slim, to allow the wheelchair to which it is attached to pass through doors; (ii) lightweight, to minimize the wheelchair load; (iii) easy to control with single input devices, such as joysticks and keypads; (iv) mechanically integrated into the wheelchair, with an integrated manipulator and wheelchair control; and (v) minimal power consumption. It has six degrees of freedom, excluding the two-finger gripper which is opened and closed by a passive spring, giving a three-point gripping action for most objects. Gripper accuracy increases with the rigidity of its fixture to the wheelchair, but power loss due to friction and backlash can make it difficult to control the arm precisely. A ball-screw mechanism translates the rotary drive into the linear movement of the gripper. It has a self-breaking effect which ensures that the gripper remains closed in the event of a power failure, preventing objects being dropped and possibly broken.

Incremental encoders are used to control the position of the manipulator. It has a range of 80 cm, a maximum gripping load of 2 kilograms with the arm extended, and a maximum gripper speed of 0.5m/s. The manipulator weighs 13 kilograms. MANUS can be mounted on an electric wheelchair or a mobile base and, when not in use, folded in beside the wheelchair. The user controls the robotic manipulator using an input device, such as a 4 x 4 button keypad or a joystick, and the same device may be used to control MANUS and the wheelchair. It has a 24 V DC power supply, but MANUS does not require extra batteries when it is used as part of an electric wheelchair.

An upgraded version called the iArm (or intelligent assistive robotic manipulator) (see Figure 3) has also been commercialized (http://www.exactdynamics.nl/site/?page=iarm). It is lighter than MANUS, at nine kilograms, and provides more control options. It uses the same battery as the user's wheelchair, to which it can be attached. It can be operated by a keypad, joystick or single button control. The Macro menu can store up to 12 user-defined positions. The Pilot menu allows the user to use a marker to draw on a whiteboard.

A number of multi-function robotic manipulators will be briefly discussed. Raptor [143] is the other commercially available wheelchair-mounted robotic manipulator. It is considerably cheaper than MANUS, but has more limited functionality and only four degrees of freedom. Its applications include eating assistance, turning switches on and off, accessing a computer and reaching objects on the floor, on a table, and above the head. It can be operated by a joystick, keypad or sip-and-puff input device and is mounted low down, at the rear side of the wheelchair. The Weston wheelchair-mounted robot [135] is mounted vertically and has an extending mechanism with two parallel vertical tracks driven by a single motor to extend its range without giving excessive height. The arm has a purpose-made gripper with two parallel moving jaws and a four-bar link mechanism. The user interface involves a joystick or similar.

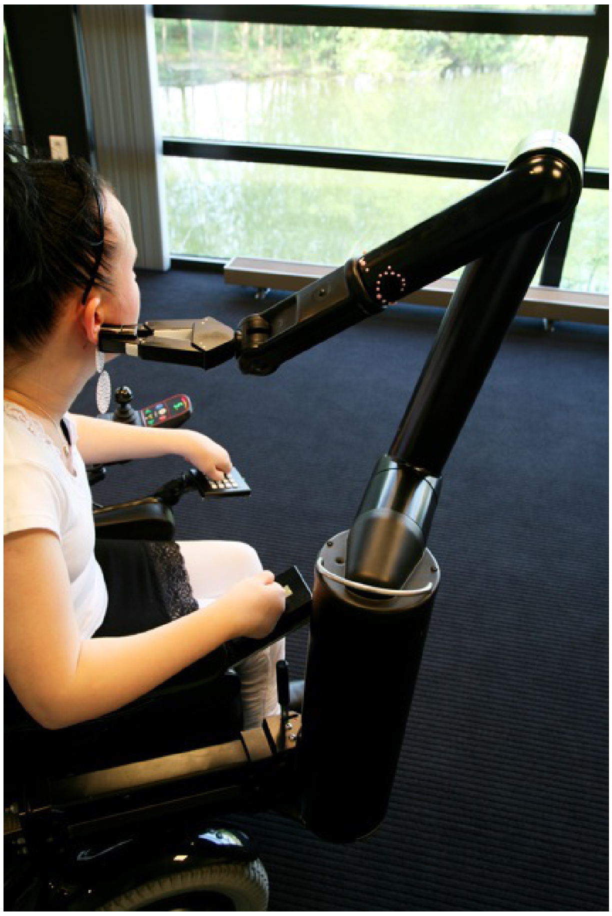

Figure 3. iArm

ASIBOT [147, 148] is a five degrees-of-freedom robot weighing 11 kilograms with a 1.3 metres reach and all control systems on-board. It is totally autonomous and can be used anywhere where there is a docking station and power supply. It can be attached to a rail fitted to a wheelchair, a mobile trolley which can move in a wall-mounted rail when it is required to move longer distances, and fixed to a particular location when required to carry out specific tasks, such as putting plates on the table. Both ends of the manipulator have conical connections which can work as a grip or fixation part to the docking station.

ProVAR [142] is an assistive desktop manipulation system with a small robot arm mounted on an overhead track suspended above a desk or work surface. It uses force-based object manipulation and is compatible with commercially available assistive technology interfaces. It can access items on the desktop and shelves on both sides and bring objects, such as a telephone receiver, closer to the user's face. RAID [141] is a robotized computer workstation intended mainly for vocational use in an office environment. Its applications include computer-aided design and other computer office tasks, such as desktop publishing, graphics layout and word processing. The original design has been modified to give more flexible end-effectors and to minimize tool changing. It is based on a 'book gripper' and 'page turner'.

ARPH [144] comprises a MANUS manipulator arm mounted on a small mobile robot for indoor use and is designed to move in a partially known environment. Planning, navigation, localization and perception tasks are implemented in Linux. The system allows for variable degrees of robot autonomy and human involvement, with the focus on higher-level functions

Handy 1 [149, 150], which is no longer in production, is a robotic system designed to aid disabled people with little or no hand movement to eat, drink, wash, shave, clean their teeth and put on makeup independently. It is used by more than 200 people worldwide. A single switch can be used to operate the system, which consists of several detachable slide-on trays and a robotic arm with changeable attachments. Trays have been developed for eating and drinking, washing, shaving and teeth cleaning, including a hot air dryer, the application of make-up, and an 'artbox' for drawing with coloured felt tip pens.

4. Sensory Assistive Devices

4.1 Mobility Devices for Blind People

Robotic devices have the potential to be used to support mobility and independent travel for blind and partially sighted people, as well as to provide physical support for, for instance, older blind people. These devices generally have a number of sensors and carry out real-time analysis of the environment and compute and follow an appropriate optimal travel direction that avoids any obstacles in the user's path. The guide changes direction when the robot detects an obstacle and communicates this change to the user by having sufficient mass for the user to feel its movement haptically through the physical interface provided by the device handle. The user intuitively reacts to changes in direction of the handle caused by the movement of the robot's wheels and is thereby steered along the desired path. This requires minimal training input, whereas specialist training over an extended period is generally required to use a long cane or guide dog safely and effectively.

Robotic guides therefore have some of the advantages of a guide dog or human guide in terms of a very intuitive guidance system based on following the robot's movements, while avoiding the need to be responsible for a dog or dependent on the availability of a human guide. In addition, a robotic guide is much easier to use and requires considerably less concentration than the long cane or devices based on it, and could give blind people who currently only go out when accompanied the confidence to do so without a human guide. It is still essential that blind travellers have a reasonable level of independent mobility skills and that they are in a position to make decisions to override the robotic device.

However, the technology is advancing and, at some point in the not very distant future, the development of robotic guides able to support blind people with limited mobility skills to travel safely should be feasible. Robustness and reliability will be very important for this type of robot, and it will be essential that there are numerous backup and failsafe features to reduce the risk of failure to as close as possible to zero. The availability of robotic guides will significantly increase the opportunities and quality of life of the numerous blind people who currently only travel accompanied, since family, professional and volunteer guides are not always available. They would also be very useful for proficient travellers in unfamiliar environments.

Robotic guides could have the further advantages of improving confidence and mobility skills, particularly for blind people who normally travel accompanied. On the negative side, robotic guides have the disadvantages of relatively high costs, though good design could reduce this, and drawing possibly negative attention to the user, unless very well designed. A recent study [21] found that potential users are particularly concerned about the appearance of a robotic guide and that they wanted it to be inconspicuous, whereas a device of a certain size is required to enable users to feel its movements, for instance to avoid obstacles, so they can easily follow it. Respondents also wanted the robot to either be unobtrusive or to have an attractive appearance. For younger users, a science fiction/robot look might work, but this would probably not be acceptable to older users. Further desirable features include an adjustable handle and a pointing device to indicate the desired direction of travel relative to the current orientation. A balance is required between the robot being light and compact so as to make it easily portable and to facilitate lifting onto public transport, and the minimum weight required for the user to feel and respond to the robot's movements. The robot should require minimal power to both extend the time it can be used between charges and to minimize battery weight. A robotic guide could also be designed to incorporate self-defence functions to increase user safety. However, considerable care would be required in the design so as to ensure that they were not used inappropriately and that the use of excessive force was avoided.

Another cheaper and more discreet option to a robotic guide would be the provision of an intelligent, contextually-aware travel assistant on a smart phone. However, this would not be able to provide physical support to the user and would require a much higher degree of independent mobility skills, as it would not provide intuitive guidance based on following the robot's movements. It would also need to be used with either a cane or a guide dog.

The earliest robotic guide was the Meldog project in 1977 [151], which only produced a first prototype. It was intended to provide a similar type of assistance to a guide dog. It followed the user's commands, but could 'intelligently' disobey them in the case of danger to the user. Many of the fairly small number of subsequent projects have been restricted to specific, generally indoor, environments. Most robotic guides try to use off-the-shelf components to reduce costs. They generally have some combination of laser range finders, infrared and ultra sonar sensors and video cameras. Many of them have on-board processing or laptops, but others only, or additionally, have off-board processing, which either reduces the robot's range or requires the laptop to be carried in a backpack.

One of the few devices which was briefly commercialized, though it is no longer available, is Guido [56] (See Figure 4). It will be discussed in this section, though it provides physical support as well as guidance functions. It is a robotic walking frame with a scooter-like appearance designed to appeal to users, and handlebars which feel like those of a bicycle. It combines the functionality of a guide dog and robust support for the user. Guido has an on-board processor, a SICK laser for sensing the environment, and a force sensor in the handle for sensing user steering. Its front wheels are steered by two motors, but it needs to be pushed by the user.

Figure 4. Guido

Guido's functions include object detection, obstacle avoidance and landmark detection without the need for a map. It combines data from the sensors with information about the device and the user's movements to select the clear path closest to the user's goal. Information about landmarks and obstacles is communicated to the user through voice messages and the steering. It has a context-sensitive user interface with haptic input and switches, and audio and haptic feedback output. Pre-recorded messages, such as the path being blocked or clear and the destination being reached or being passed, assist the user in controlling Guido. It can be used in automatic mode, in which it uses its full capability to avoid obstacles, and manual mode in which the user retains full control of the device, but it can have voice feedback. In response to user requests, Guido was provided with physical brakes as well as automatic braking.

A number of other robotic guides have been developed but have not got beyond the prototype stage. The Smart-Robot [152] has four wheels and a chassis. It uses RFID and GPS localization indoors and outdoors, respectively. The robot continuously checks for obstacles using ultrasonic and infrared sensors and computes a new route to avoid obstacles, presenting continuous feedback to the user through the speaker and vibrating motors on the glove. Landmark information is also announced by the speaker.

RG-I [153, 154] is intended to be used in supermarkets, airports, conference venues, hospitals and other institutions rather than being owned by individuals. It requires small, passive RFID sensors to be located in the environment and it is not suitable for navigating large open spaces, such as hotel lobbies. Haranobu 6 [155, 156] consists of a motorized wheelchair platform which the user follows. It uses a geographic information system in navigation and detects pedestrians by their rhythmic movement and cars by the shadows under them.

The GuideCane comprises a robotic wheeled base with 10 ultrasonic sensors for obstacle detection at the end of a cane which the user holds [54] (Ulrich and Borenstein, 2001). The wheels can be steered to the left or right relative to the cane by a servomotor controlled by the built-in computer. The user can indicate a desired direction of motion by pressing a mini joystick in the handle in that direction. When the wheels turn sideways to avoid an obstacle, the user almost automatically changes orientation to follow the cane. The GuideCane is semi-autonomous, with full autonomy for obstacle avoidance, and it uses the user's skills for path planning and localization. It has not gone beyond the prototype stage and its appearance and cumbersome size could act as barriers to further development unless modified.

Another guide has a pan-tilt camera on the base of the autonomous robot Leo-1. The camera images are processed and used to operate the robot, with processing including a four-directional features field and a character recognition system with verification to read, for instance, room numbers [157]. The Hitomi [158] consists of a powered wheelchair with a camera, ultrasonic and tactile sensors, and GPS to guide the user in outdoor environments. It is intended for people with sight loss later in life, and the user follows the chair, holding onto the handles.

4.2 Shopping Assistance Robots

Blind people require assistance either from technology or a person to locate and identify products and to read information about them, such as prices and ingredients. Both robotic and software-based shopping assistants for blind people have been developed. The software-based systems include [159, 160, 161, 162, 163] BlindShopping, GroZi, iCode, ShopCode, ShopMobile, ShopTalk and Tinetra. These systems detect and identify products using barcode scanners, RFID readers and cameras which read quick response (QR) matrix barcodes. The software is installed on, for instance, a mobile or smart phone or a mini PC in a backpack, and some of the systems provide navigation instructions. These systems have the advantages of being easily portable and of not drawing attention to the user, and are probably considerably cheaper than robot systems. However, robotic applications have the advantage of being able to provide additional functions, such as guidance and support for the user, bringing products to the user and carrying them.

RoboCart [164, 165, 166] has two main functions: guiding a blind shopper to the vicinity of a product, and haptic exploration to find the product supported by the locomotor and haptic modules, respectively. It consists of a mobile robotic base with a wayfinding toolkit in a PVC pipe structure which also provides a handle, and a basket mounted on this structure. The rigid handle provides haptic feedback about the robot's movements. A 10-key numeric keypad in the handle allows the user to browse a list of products or enter a product number. When the shopper is close to the product, the robot tells them how to find the product in synthetic speech using their egocentric (body-based) frame of reference. The robot uses Monte Carlo Markov localization with RFID mat recalibration points read by an RFID antenna close to the floor. The need for RFID mats is one of the disadvantages of the device. Comments from participants in user tests [166] indicate that they want to know what products they are walking past, with more detailed information on how to find the product after scanning the barcode, and for the robot to stop either directly in front of or just past the product (depending on the presence of other shoppers and other obstacles) and beep rather than make clicking sounds, which are both irritating and easily missed in the background noise.

Robotic shopping assistants designed for guiding non-disabled shoppers could be used to support visually impaired people if appropriately modified. However, they are only able to guide users to the approximate location of the products of interest, rather than aiding them in locating a particular product or providing information about other similar products to enable comparisons. An example is Toomas [9], which has been trialled in large home improvement stores in Germany. It is 1.5 m high and weighs 75 kilograms, and is designed to work autonomously. It has a differential drive and castor on the rear and a maximum speed of 1.4 m/s. An omnidirectional camera on the top of its head delivers panoramic and high-resolution frontal images, and 24 sonar sensors at the bottom carry out obstacle detection, map building, localization and person-tracking (to identify shoppers). A laser range finder was added to meet German safety regulations. Toomas has a three-layer control architecture which separates the robotic-specific methods and skills from the application.

5. Socially Assistive Robots

5.1 Companion and Socially Assistive Robots

Social robots are designed to produce social behaviours and perceptions in people [19]. They draw on the human tendency to anthropomorphize objects [167], giving rise to feelings for them, and they proactively engage with people and/or show some degree of social intelligence [168]. Socially interactive robots are a type of social robot for which the social interaction between the human and the robot is particularly important [73]. They may perceive and/or express emotions, use high-level dialogue in communication, recognize other agents, establish and/or maintain social relationships, have 'personality' and 'character', and they may be able to learn social competencies.

Socially assistive robots are a type of social robot [19, 169] which provide assistance to end-users through social interaction. The human tendency to attribute human intentions and goals to even very simple mobile physical entities may make companion and socially assistive robots more effective than a programme on a computer or mobile phone [170]. A classification framework for social robots based on the following five properties has been proposed [169]: (i) form from abstract through animal-like to human-like; (ii) modality or number of communication channels; (iii) extent of knowledge of social norms; (iv) degree of autonomy; (v) interactivity or extent of causal behaviour. Socially assistive robotics support users through social interaction [171]. They are designed for emotional expressiveness, user engagement, appearance and robustness during interaction, in order to assist the user and influence their behaviour [171].

Feil-Seifer et al.'s [172] benchmarks for socially assistive robots are stated below with 'carer' replaced by 'personal assistant', as this has a wider meaning:

1. Technology properties: (i) safety; (ii) scalability or the ability to translate effects found in the lab environment and to different numbers of users and users with different needs.
2. Social interaction properties: (i) autonomy; (ii) privacy; (iii) role in the community; (iv) frequency and success of social interaction.
3. Assistance properties: (i) impacts on the user's life; (ii) impacts on personal assistants' lives; (iii) impacts on the effectiveness of the support provided.

There have been a number of generally small-scale studies of the use of assistive social robots with elderly people [173], with most of the studies carried out in Japan with the dog robot AIBO [174] and the baby harp seal robot Paro [175, 176] (see Figure 5). Despite study limitations, many of the studies have shown positive effects from either the use of a robot or a non-functional robot or pet toy, as well as that older people are open to the use of robot technology [173]. However, it has been suggested [5] that, at least in some cases, the positive effects may be the result of an almost total lack of stimulation in their daily lives such that anything new is welcomed. In addition to AIBO and Paro, robots which have been used in studies of socially assistive robots include the cat robots, iCat [177] and NeCaRo, the humanoid robots, Bandit and Brian [178], and the machine-like robots with some humanoid features, Pearl [179, 180] and the companionable robot companion [39].

Figure 5. Paro

AIBO, which is no longer in production, has a hard plastic exterior, a camera, touch sensors, infrared and stereo sound, four moveable legs, a moveable tail and a moveable head. It can walk, chase a ball, is autonomous and has programmable behaviours. It uses its tail, body movements and the colour and shape of its eyes to express six 'emotions'. Its sensors are able to detect distance, acceleration, sound, vibration and pressure. Later versions are able to recognize voice commands. The iCat is made of hard plastic with a cat-like appearance and a face able to express some emotions. It is intended for functional assistance rather than companionship, and as a research platform for human-robot interaction. NeCeRo is covered in synthetic fur, can 'learn' to recognize its name, responds positively to stroking and hugging and negatively to rough treatment. Paro was chosen to be an unfamiliar animal in order to avoid raising expectations and was designed specifically for therapeutic uses with elderly people. It has a ubiquitous tactile sensor between its hard inner skeleton and white fur to make it feel soft, an infrared sensor, stereoscopic vision and hearing, and a light sensor to detect light and dark. It makes seal-like sounds and moves its tail and opens and closes its eyes in response to petting. It is not mobile but it can move its neck, front and rear paws and eyelids, which contributes to its facial expressions [181]. Both Paro and NeCeRo 'sleep' or seek to be cuddled in response to internal rhythms.

Bandit and Brian both consist of a humanoid torso on a mobile robotic base. Bandit has 19 controllable degrees of freedom. A USB camera at the robot's waist captures the user's arm movements to enable the provision of performance feedback using speech generated by the commercially available NeoSpeech text to a speech engine [182]. Brian produces facial expressions through the activation of facial 'muscles' in four groups at the control nodes. Its skin is silicone rubber so as to make it elastic and thus permit considerable deformation when expressing 'emotions'. Pearl is a second generation mobile nursebot that can assist elderly people in navigating a nursing home. The companionable robot companion has a tiltable touch-screen for graphical and touch-based communication with the robot, a tray for personal items, and two OLED displays as eyes to allow simple facial expressions. It has a number of autonomous behaviours, including detecting, tracking and searching for the user, both in the user's favourite places and the whole flat. However, this may raise issues of control and surveillance and whether this is carried out at the instigation of the user or someone else.

Suggested potential uses of socially assistive robots include encouraging post-stroke exercising and rehabilitation [183, 184] and supporting people with dementia [181, 185, 186, 187]. Small-scale trials have found that the robot did motivate exercise, though there were significant differences in responses. A review of the studies of the use of socially assistive robots with people with dementia [186] found that the animal robots NeCoRo, Paro and AIBO led to increased social interaction and reduced stress (as measured by physiological symptoms), and that they reduced staff burn-out when used in a day care centre, while Bandit also had some positive effects when programmed to stimulate positive responses in a musical game. However, in another study, while Paro was found to calm an elderly man with moderate dementia, this involved giving him the false impression that Paro was alive, which raises important ethical issues about honesty, respect and not potentially increasing feelings of confusion. There is also the possibility that these robots have a calming effect by masking symptoms, and that they thereby prevent attention being given to the underlying causes.

Socially assistive robots could have potential benefits for at least some elderly people, but they also raise a number of serious concerns, many of which are summarized in [5]. The possible use of deception and diverting attention from possibly serious problems have already been mentioned. Concerns about the substitution of real contact with people by robots are discussed in Section 7, which addresses user acceptance. As in the case of the smart house, there is also the potential to use these robots for surveillance and to control an elderly person's activities. As indicated in [5], there is also the possibility that robots will be used in ways that demean and infantilize elderly people. There is therefore a need for further research on the use of socially assistive robots in ways that are acceptable to elderly people and which remain within their control. There would also be value in the development of a taxonomy of socially assistive robots which relates robot characteristics to user characteristics and preferences, and the specific functions and context in which the robot is used.

5.2 Robots for Autistic Children

The use of robots with autistic children is another area which has potential but which could also give rise to problems. Robotic toys to be used by disabled children need to be very robust, and autistic children may prefer a robot without facial features to one that looks human [188]. The investigation [189, 190] of peer-reviewed studies of the interactions of autistic children with robots indicates the potential of robots to elicit various types of behaviour, but further research is required. The following robot design specifications have been suggested [191]; (i) approximately the size and weight of a commercial doll, i.e. about 50 cm high and 1 kilogram in weight; (ii) low cost, to allow purchase by collaborating schools and museums; (iii) on-board processing and battery operated; and (iv) a resemblance to commonly-used toys. It has been suggested that a human-seeming body and features can bridge the gap between non-human-looking machines with which autistic children feel comfortable and people where the interaction is more difficult [191]. Research is investigating whether social interaction with robots can be translated into improved social interaction with other people e.g. [19].

A number of different robots, both research prototypes and (modified) commercially available robots, have been used with autistic children, but their use is still at the research stage. They include humanoid, generally toddler or small child sized robots animal robots and objects. NAO [192, 193] (see Figure 6), Kaspar [194] and Robota [191, 195] are three toddler- or small child-sized humanoid robots. Both Kaspar and Robota are designed to be low cost and generally wear clothes which cover the robotic parts, as well as a wig. NAO is 0.57 metres high and weighs 4.5 kilograms. Its patented pelvis kinematic design only requires one motor and allows it to simultaneously bend forward and move its legs apart. Its sensors include cameras in the head, capacitive feedback to receive 'tactile' input from contact, two gyrometers and three accelerometers for real-time data acquisition. The Choregraphe software provides text-to-speech conversion, sound localization, visual pattern and coloured-shape detection, obstacle detection and visual effects, which are output through its LEDs. NAO has 25 degrees of freedom, five in each leg and arm, one in each hand, two in the head and one in the pelvis. Both Robota and Kaspar are designed to be low cost.

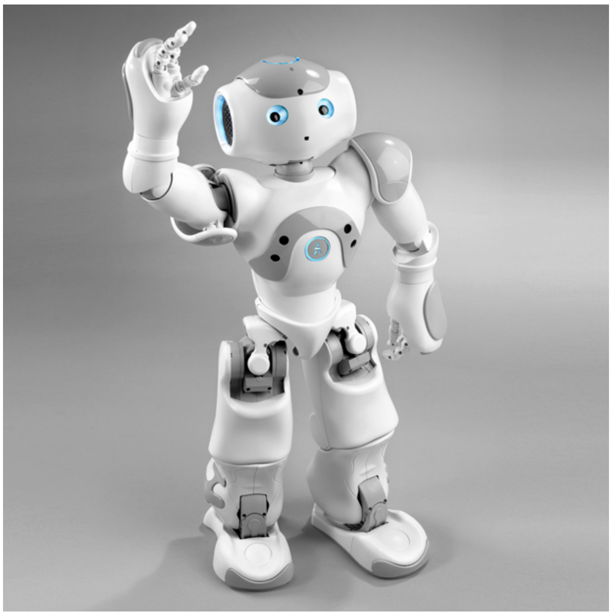

Figure 6. Nao

Kaspar is a stationary humanoid robot which is 'minimally expressive' to avoid presenting too many social cues while providing facial expressions for autistic children to interpret. It is the size of a small child with a large head. Its body is based on a child-sized shop floor dummy and its face is a silicon rubber face mask from a child resuscitation practice dummy. It is flexible enough to be deformed by actuators and it provides simplified human features. Kaspar's main moving parts are the head, neck and arms with the joints activated by radio-controlled model servos. Robota is a 45 centimetre high humanoid robotic doll weighing 1.6 kilograms and containing a PIC motor, sensor boards and drivers. The initial prototype was made of Lego parts. The current commercially available version sold for $3,000 in 2006. A serial link connection to a PC enables Robota to use speech synthesis, speech processing and data processing from a quick-cam camera. It can copy some of the user's movements.

Roball [196] is an autonomous ball-shaped rolling robot which rotates on all its surface, not just a wheel. It is about 15 cm in diameter and it weighs less than two kilograms. The sturdy flat-topped Labo-1 mobile platform [197] has eight infrared sensors for obstacle avoidance and a single positional heat sensor. It has a main control module which controls the selection of four behaviours involving movement in different directions. Pleo [19] is a small commercially available toy dinosaur robot, about 53 cm long and 20 cm high. It uses body movement and vocalizations to express emotions and attention. It is battery powered with 15 degrees of freedom and can be controlled by a handheld remote control and a built-in infrared receiver in its snout. It can support 13 custom pre-recorded behaviours involving synchronized movements and speech-like recordings. Some of the behaviours are designed to be socially expressive.

On the one hand, there are indications that robots can be used to support the development of competencies in interaction and communication, and that autistic children are using the robots as a 'mediator' to support interaction with the experimenter or other children [168, 195]. On the other hand, there may be attempts at behaviour modification in order to try and 'normalize' the children rather than focusing on developing innate strengths and competencies, which help them to function in what is often a not particularly friendly world.

6. Mixed Assistance Robots

6.1 Robotic Assistants for Elderly People

Surveys have identified that older people, their relatives, assistants and (other) professionals are interested in a companion robot having the following functions [39]: (i) communication with family, personal assistants and professionals; (ii) safety functions, including medication reminders, monitoring and fall detection and remote control of the robot to evaluate critical situations; (iii) cognitive training functions and stimulating games; and (iv) smart contextual awareness to allow the robot to adapt its behaviour to the user's needs. However, it should be noted that contextual awareness raises issues of the trade-offs between privacy and adaptation. In addition, it was personal assistants rather than elderly people who were interested in safety information [198], and it is important that the worries of family and professionals do not result in monitoring and restrictions that elderly users do not want. Fulfilling users' requirements requires human-robot interaction, navigation and assistive services. It has been suggested that interaction requirements should include [39] the abilities to: (i) detect and track a moving/static person; (ii) autonomously search for, face towards and follow the user; (iii) understand a given set of words and critical sounds e.g. glass shattering; (iv) notice items in its tray; and (v) have simple emotional facial expressions. However, users may prefer a robot that concentrates on social interaction and which does not search for and monitor them.

Although, as indicated by the sales figures, there has not yet been a significant movement in this direction, the more industrialized countries with an aging population may increasingly investigate the use of robots to assist elderly people. For instance, a Japanese Trade and Industry Ministry official indicated in 2009 that there would soon be a need to prepare safety rules for robotic nurses expected to serve elderly people in the next five years [5].

Care-O-Bot is a home robotic assistant which was developed iteratively from a mobile platform with a touch screen [199]. The main components of Care-O-Bot 3 (see Figure 7) [200, 201] are a mobile base, a torso, a lightweight robotic arm with a three-fingered gripper which can reach the floor and high cupboards, a tray for passing objects between the robot and the user, and sensors on a carrier. The robot has 28 degrees of freedom and the arm has seven. It has four wheels rather than legs to increase stability and reduce the risk of falling. Laser scanners on the front and rear support navigation and collision avoidance. It requires training to recognize objects. The control software for the mobile platform is a hierarchical multilayer system. Subsequent robots in the family have been developed [202] based on a modular design with arms from different vendors and different sizes of mobile base and torso as well as different sensor configurations. However, they are being used as a standard platform for research on mobile manipulators and their applications rather than being implemented in practice.

Figure 7. Care-O-Bot 3

The similarly named CareBot [5] can carry out simple verbal interactions, give reminders at predetermined times and dates, give medicine and monitor the user's state of health using its vital signs sensors, and follow the user from room to room. However, its role could be more to monitor rather than assist an elderly person. The uBot5 [203] can lift and move objects and carry out other tasks using its manipulators. It can be remotely controlled over the Internet to carry out tasks, including to monitor the user for signs of a fall.

The Nursebot project was originally intended to develop robotic assistants for elderly people – particularly those with mild cognitive impairments – in their own homes, but it has expanded to cover other settings. It has developed two autonomous robots, with the current one called 'Pearl', and supporting software. Its main functions are to provide reminders with some flexibility to take account of the user's schedule, and support navigation about the environment. However, it collects data about the user's activities [180]. This can be supportive, for instance in giving a reminder to take medicines after an appropriate length of time following eating, but it is intrusive and the user may not be aware of what data is being collected about them. The Pam-Aid provides physical support and obstacle avoidance for older blind people [204, 205].

The personal aids for the mobility and monitoring [12, 206, 207] (PAMM) concept provides physical support and guidance, including obstacle avoidance using a detailed map from a central computer, and health monitoring. An upward-looking camera is used for localization. Sensors continuously monitor the user's vital signs. Implementations include the SmartCane (which has too large a base to act as a cane) and SmartWalker, which provides support. It is intended to delay the move from an assisted living facility to a nursing home [207], but the assistance provided does not necessarily either require or justify the monitoring involved.

Riba (Robot for Interactive Body Assistance) has a teddy bear face and can lift and move people from a bed to a wheelchair, recognize faces and voices, and respond to spoken commands [5]. EI-I [208] is able to respond to simple commands and carry out tasks in the house analogously to an assistance dog. It can open doors and drawers indicated with a coloured towel tied to them when instructed verbally, with a laser pointer used to indicate the location, as well as lift objects off flat surfaces.

It should be noted that mixed assistance robots raise similar concerns to those discussed in Section 5.1 for socially assistive robots for elderly people.

7. User Acceptance of Robots

As discussed in the previous sections, there are many different applications of assistive service robots, but they are fairly rarely encountered in practice. While robots are not suitable for all applications, there seems to be a considerable gap between the potential and the number used in practice, as discussed in Section 1, even taking into account the fact that many assistive robots are prototypes and do not appear in sales figures. There are a number of reasons for this, including the fact that the majority of these robots do not get beyond the prototype stage, as well as the relatively high costs of many of the systems which are commercialized.

There are also issues of user acceptance. The increasing possibilities of service robots have led to a number of studies of robot acceptance. Acceptance has been defined as the 'demonstrable willingness within a user group to employ technology for the tasks it is designed to support' [209]. It has also been noted [210] that acceptance generally involves a combination of positive evaluation, intentions to use the technology and actions when using it, called 'attitudinal', 'intentional' and 'behavioural' acceptance respectively. One of the earliest studies of the user acceptance of robots related to a robotic arm in a clinical setting [211].

A large-scale survey [212, 213] of younger and older adults found that both groups had greater acceptance of robots performing infrequent but important tasks that required little interaction, and the least acceptance of robots for non-critical tasks requiring extensive interaction. The older adults (aged 65-86) exhibited greater acceptance of robots performing critical tasks in their homes. The authors also found that both younger and older adults considered robots mainly as machines to perform tasks rather than to interact socially with. A study involving over 2,000 participants [24] found that women were less willing to accept robots than men, and that elderly people had the best image of robots of any age group. They showed a combination of scepticism of new technologies and concern for improving their quality of life. They were therefore the group most interested in using a robot to regain independence, but least interested in a robot purely to free them from particular tasks.

This may relate to the fact that saving time is less an issue for elderly than working-age people, whereas they feel their independence is threatened and are very concerned about maintaining it. Interestingly, elderly people preferred human assistance to robotic assistance in terms of autonomy. However, the issue here may be concerns about loneliness and social isolation, again indicating that robots should not be used to replace human companionship. This is further borne out by the findings [26] of three focus groups with older people (aged 65-89), some with mild cognitive impairments, that the participants were concerned about, and even afraid of, contact with robots being substituted for contact with people and robots and robotics projects being funded rather than human assistants for older people. Although they considered the seal robot Paro charming, interaction and communication with it were 'not... genuine' and 'communicat[ion] with nothing.' While the participants did not like humanoid robots, they reacted positively to small robots that they considered creative and which had human traits [26]. While much of the discussion of the acceptance of assistive robots has focused on socially rather than physically assistive robots, issues of the possible withdrawal of funding for personal assistance due to the potential or actual availability of robots is of concern in both cases.

A number of studies have been carried out of socially assistive robots, often involving animal robots. However, care needs to be taken in interpreting the results and the extent to which they transfer to other contexts, groups of users or types of robots. In most cases, further research will be required. The experience of meeting a robot was found to lead to more positive attitudes towards robots among older people and staff in a retirement village [214]. There are also indications from studies of greater acceptance, psychological closeness and/or more positive reactions to robots which are more similar to users. This includes with regard to 'gender' as indicated by the robot's voice, as in one study involving students [215], and 'personality' in the case of post-stroke rehabilitation therapy [184] and small numbers of disabled people [183].

Both appearance and behaviour can affect the responses to robots, but there have been more studies of the impact of appearance than behaviour. Studies have shown that, for instance, blind people consider the robot's appearance important [21]. Preferences for a humanoid or machine-like robot have been discussed in Section 2.1. It has been suggested that appearance is particularly important in determining reactions to the robot in the case of short-term interactions, for instance, in demonstrations and exhibitions, whereas in the case of long-term interactions in the home, at school or in a nursing home, the robot requires a learning function to change its interaction in order to avoid the person becoming bored [216].

Studies have found that older people in an institutional setting were excited about the presence of a robot [179]. Several studies have shown that users preferred communicating with and enjoyed the communication more when animal and humanoid robots exhibited more social behaviours, such as looking at the user rather than past them [217, 218], using the user's name, greeting them and saying farewell, and varying the wording in therapy-encouragement messages [182]. In addition, the perceived enjoyment and intention to use robots have been found to be correlated with actual use [219, 220].

There have been two main approaches to modelling acceptance or attitudes towards technology which are relevant to assistive robots: (i) a number of different technology acceptance models; and (ii) two attitudes towards robot scales. For some reason, the technology acceptance models focus on the positive factors, such as perceived usefulness, ease of use, facilitation of tasks and the (positive) social influence of other people's perceptions of information technology use, whereas the two robot attitudes scales have only negative factors. The earliest and simplest model (and which has some empirical support [69]) is the Technology Acceptance Model [210]. Other models include the Unified Theory of Acceptance and Use of Technology Model [221] and the Technology-to-Performance Chain Model [222].

The Negative Attitude to Robots (NARS) [223, 224] and the Robot Anxiety Scale (RAS) [225] have been used to study negative reactions and anxiety in response to humanoid and non-humanoid robots. Both scales have three dimensions. NARS considers negative attitudes towards interaction and emotional interaction with robots and robots' social influence. RAS considers anxiety about robots' communication and behavioural capabilities, and anxiety about discourse with robots. It would seem appropriate to combine the two approaches to consider both the positive and negative factors which affect robot acceptance and use. Other factors which can affect acceptance and which are not included in the technology acceptance models [69] include: (i) functionality, including the tasks the robot or technology can carry out; (ii) the degree of autonomy and the type of interaction and control; (iii) social ability, including facial and other expressions or emotional and non-verbal social cues; (iii) form and appearance, including whether the robot resembles a person e.g. has a human-like face, body, arms and legs, height and gender for human-like robots, and whether it looks like an animal or an object for non-humanoid robots.

There are also multi-level approaches, such as the two-level Almere Model [226]. It is related to the technology acceptance models, but it also includes the negative factor of anxiety at the first level. Other factors include trust, perceived adaptability, social abilities, perceived enjoyment, usefulness and ease of use. In the case of assistive robots, an appropriate degree of autonomy is required so that users do not feel the robot is taking control away from them or making high-level decisions for them. However, the robot requires sufficient autonomy to appropriately support the user. Autonomy levels can affect robot acceptance, as they may determine its perceived usefulness. For instance, a robot that cannot navigate accurately around the home may be considered useless despite its other abilities [69].

The impact of perceived stigma has been ignored in both the studies and the models of robot acceptance. This is particularly relevant to assistive devices [227], possibly including assistive robots. While there is a body of general literature on stigma e.g. [228, 229, 230], most of the literature on stigma and assistive devices relates to hearing aids and is not recent e.g. [231, 232], with a small number of exceptions e.g. [233]. Social acceptability is an important factor in determining whether assistive technology is used or abandoned [227], and fears of stigmatization may lead to difficulties in accepting it and to non-use or attempts to make it invisible, for instance by using a folded long cane, which reduces its usefulness [227]. This is a much stronger effect than the social influence of other people's perceptions, which appears in one of the technology acceptance models and which is only considered from the positive perspective. However, robots are still a relatively new and advanced technology, with futuristic and science fictional associations. This may lead to the possession or use of an advanced robot conveying status, which counteracts the stigma associated with assistive devices. However, further research will be required to investigate this.

Another important factor which may affect the acceptability of assistive robots is related to personal assistance. There are at least three aspects of this: (i) the availability of personal assistance; (ii) personal preferences for robotic and personal assistance for particular tasks; and (iii) concerns that the possibility of the robotic automation of assistance may remove funding for personal assistance. As discussed above, personal assistants fulfil a social role which cannot fully be met by robots. Therefore, attitudes towards assistive robots will be strongly influenced by perceptions as to whether they will be complementary to or replace personal assistants.

Further research is still required into the factors that affect the use of assistive robots, including user acceptance. There is also a need for models of user acceptance which combine positive and negative factors. Since there are generally trade-offs between model complexity and explanatory power, simpler models are frequently able to explain a considerable part of the variation, and there could be some value in the development of simple and detailed models involving both just a few and also a much larger number of variables respectively.

The following six factors are proposed for the simple model, though further research will be required to validate the model and investigate its use. It should also be noted that several of the factors can have either a positive or a negative impact:

1. Functionality and the extent to which this meets the user's needs
2. Perceived need
3. Appearance
4. Perceived usefulness
5. Fears about isolation and loss of personal assistance
6. Perceived stigma

8. Conclusions

The paper has provided an overview of some of the applications of assistive robots. The discussion of assistive robots was structured by organization into the four categories of: (i) physically assistive robots; (ii) socially assistive robots; (iii) sensory assistive robots: and (iv) mixed assistance robots. A more detailed categorization based on assistive technology models [2, 10] has been proposed.

The discussion of different types of assistive robots was introduced by an overview of some of the underlying technologies used in assistive robots. However, a full evaluation of the state of the art with regards to these technologies was not provided, and this would require further work.

The paper has illustrated the considerable potential of robots to support and assist elderly and disabled people. However, this potential is largely untapped with only small numbers of robots in actual use, many projects not getting beyond the prototype stage, and a number of assistive robots being used as platforms for research rather than being made available, commercially or otherwise, to potential users. The applications discussed are able to support various groups of disabled people in the home or workplace, in leisure activities and in facilitating travel, whether through guidance or the provision of other smart functions. Greater availability of these applications could have a significant positive impact on the lives of disabled people. Although robots may not be suitable for all potential applications, the current application areas seem relatively limited and the examination of the various models of human activities e.g. [2, 234, 235], indicates that there may be a wide range of other application areas that have not yet been investigated.

On the other hand, not all potential applications of assistive robotics are positive, and there is a need for assistive robots to be used appropriately. There are probably greater concerns about socially assistive robots than there are about physically assistive robots. However, in both cases there are issues of the substitution of personal assistants by robots rather than the two approaches been seen as complementary and both being available, so that users can make appropriate choices for their particular circumstances. For instance, as discussed in Sections 3.2 and 3.3, robotic devices are able to support many self-care activities, though applications able to aid in dressing do not yet seem to be available. When used appropriately, such robotics applications can significantly improve the options and choices available to potential users. However, the use of personal assistance to carry out self-care tasks may be faster, making more time available for work, study and leisure activities.

In the case of socially assistive robots, elderly people in particular have serious concerns that robots will replace personal contact and personal assistance, leading to a loss of companionship and increasing isolation, though there is also some evidence of these robots providing the focus for increased positive social interaction with other people. These concerns are very real and need to be taken seriously. Regardless of future technological developments, it seems unlikely that interaction with a robot will ever have the same quality as interaction with a person (or animal). The nature of the interaction with an animal and other toy robots may also be problematical and based on the deception that the robot is real [5]. Another area which gives rise to serious concerns is the proliferation of sensors, the monitoring of the occupant and the collection of personal data in smart home applications. This raises a range of privacy management issues, as well as the rights of elderly people to make choices and take risks.

In summary, assistive robots have considerable potential to support disabled and elderly people, but this requires them to be used sensitively and appropriately. In particular, they should be seen as being complementary rather than as a replacement for personal assistance. This issue and concerns about loss of contact with real people emerged vividly in the brief discussion of user acceptance. It was noted that the approaches to modelling user acceptance consider either positive or negative factors, but not both. A new model of user acceptance, including both positive and negative factors was proposed, but further work will be required to validate it.

There is a need for further research in a number of different areas, including: user involvement and requirements; user acceptance and use of assistive robots; development of the underlying technologies; development of applications; privacy management; and outcome evaluation. User involvement is essential to determine what applications are likely to be of interest to disabled and elderly people and to determine their requirements, while recognizing that each user of assistive robotics is an individual with their own specific needs and preferences. User involvement in all stages of the process of the design, development and implementation of assistive robots is crucial in ensuring that users are in control of the ways in which robots are used to support them. There may be a need for the development of new methodologies for user involvement, particularly for determining the wishes of elderly people with dementia. There is a need for the investigation of both the factors which affect user acceptance and attitudes to robots and improved models.

Continuing progress is being made in both the underlying technologies and their applications, to the extent that any state of the art overview is very soon out of date. However, there remains a need for further work in many areas, including stable walking mechanisms, control architectures, artificial intelligence, speech recognition, brain-computer and other types of interfaces, and shared control. There is also a need for both the development of robotic applications in new areas and the development of existing application areas, such as robotic wheelchairs, beyond the prototype stage, in order to give potential users a wider range of choices. Research into privacy management should have at least two main components: (i) the investigation of users' concerns and the trade-offs that they are and are not willing to make; and (ii) the development of improved privacy management systems.

9. References

[1] UN (2002). United Nations and the International Federation of Robotics. Proceedings of the World Robotics 2002, New York.

[2] Hersh, M. A., and Johnson, M. A. (2008). On modelling assistive technology systems part I: modelling framework, Technology and Disability, vol. 20, no. 3. pp. 193-215.

[3] Brose, S. W., Weber, D. J., Salatin, B. A., Grindle, G. G., Wang, H., Vazquez, J. J., and Cooper, R. A. (2010). The role of assistive robotics in the lives of persons with disability. *American Journal of Physical Medicine and Rehabilitation*, *89*(6), 509-521.

[4] Burgar, C. G., Lum, P. S., Shor, P. C., and Van der Loos, H. F. (2000). Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience. *Journal of Rehabilitation Research and Development*, *37*(6).

[5] Sharkey, A., and Sharkey, N. (2012). Granny and the robots: ethical issues in robot care for the elderly. *Ethics and Information Technology*, *14*(1), 27-40.

[6] Kopacek, P., and M. A. Hersh (2014). Roboethics. In M. A. Hersh, Engineering Ethics, Environmental and International Stability. Springer Verlag.

[7] Connell B. R., Jones M., Mace R., Mueller J., Mullick A., Ostroff E., Sanford J., Steinfeld E., Story M., and Vanderheiden G. (1997) The principles of universal design version 2.0. http://www.design.ncsu.edu/cud/about_ud/udprinciplestext.htm. Accessed on 11 Aug 2010.

[8] Harmo, P., Taipalus, T., Knuuttila, J., Vallet, J., and Halme, A. (2005, August). Needs and solutions-home automation and service robots for the elderly and disabled. In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on* (pp. 3201-3206).

[9] Gross, H. M., Boehme, H., Schröter, C., Mueller, S., Koenig, A., Einhorn, E., Martin, Ch., Merton, M., and Bley, A. (2009). TOOMAS: interactive shopping guide robots in everyday use-final implementation and experiences from long-term field trials. In *Intelligent Robots and Systems, IROS 2009. IEEE/RSJ International Conference on* (pp. 2005-2012).

[10] Cook, A. M., and Polgar, J. M. (2007). Cook and Hussey's Assistive Technologies: Principles and Practice, Elsevier Health Sciences, Third ed.

[11] Goodrich, M. A., Olsen, D. R., Crandall, J. W., and Palmer, T. J. (2001). Experiments in adjustable autonomy. In *Proceedings of IJCAI Workshop on Autonomy, Delegation and Control: Interacting with Intelligent Agents* (pp. 1624-1629).

[12] Yu, H., Spenko, M., and Dubowsky, S. (2003). An adaptive shared control system for an intelligent mobility aid for the elderly. *Autonomous Robots*, *15*(1), 53-66.

[13] Fong, T., Nourbakhsh, I., and Dautenhahn, K. (2002). A survey of socially interactive robots. Concepts, design and applications. Report CMU-R1-TR-02-29, Robotics Institute, Carnegie Mellon University.

[14] Libin, A. V., and Libin, E. V. (2004). Person-robot interactions from the robopsychologists' point of view: the robotic psychology and robotherapy approach. *Proceedings of the IEEE*, *92*(11), 1789-1803.

[15] Severinson-Eklundh, K., Green, A., and Hüttenrauch, H. (2003). Social and collaborative aspects of interaction with a service robot. *Robotics and Autonomous systems*, *42*(3), 223-234.

[16] Ricks, D. J., and Colton, M. B. (2010, May). Trends and considerations in robot-assisted autism thera-

py. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on* (pp. 4354-4359). IEEE.

[17] Pioggia, G., Igliozzi, R., Sica, M. L., Ferro, M., Muratori, F., Ahluwalia, A., and De Rossi, D. (2008). Exploring emotional and imitational android-based interactions in autistic spectrum disorders, Journal of CyberTherapy and Rehabilitation, vol. 1, issue 1, Spring 2008, pp. 49-61

[18] Kozima, H., Nakagawa, C., and Yasuda, Y. (2005, August). Interactive robots for communication-care: A case-study in autism therapy. In *Robot and Human Interactive Communication, 2005. ROMAN 2005. IEEE International Workshop on* (pp. 341-346).

[19] Kim, E. S., Berkovits, L. D., Bernier, E. P., Leyzberg, D., Shic, F., Paul, R., and Scassellati, B. (2013). Social robots as embedded reinforcers of social behavior in children with autism. *Journal of autism and developmental disorders*, *43*(5), 1038-1049.

[20] Dautenhahn, K., and Werry, I. (2004). Towards interactive robots in autism therapy: Background, motivation and challenges. *Pragmatics and Cognition*, *12*(1), 1-35.

[21] Hersh, M. A., and Johnson, M. A. (2010). A robotic guide for blind people part 1: a multi-national survey of the attitudes, requirements and preferences of potential end-users, Applied Bionics and Biomechanics, vol. 7(4), pp. 277-288.

[22] Hersh, M. A., and Johnson M. A. (2012). A robotic guide for blind people part 2, Applied Bionics and Biomechanics, vol. 9, pp. 29-43.

[23] Mori, M. (1970). The uncanny valley. *Energy*, *7*(4), 33-35.

[24] Arras, K. O., and Cerqui, D. (2005). Do we want to share our lives and bodies with robots? A 2000 people survey. Technical Report Nr. 0605-001, Autonomous Systems Lab, Swiss Federal Institute of Technology, Lausanne.

[25] Oestreicher, L. (2007). Cognitive, social, sociable or just socially acceptable robots? Proc. 16th IEEE international symposium on robot and human interactive communication RO-MAN, JejuIsland, Korea, 2007, pp. 558–563.

[26] Wu, Y. H., Fassert, C., and Rigaud, A. S. (2012). Designing robots for the elderly: Appearance issue and beyond. *Archives of Gerontology and Geriatrics*, *54*(1), 121-126.

[27] Kiesler, S., and Sproull, L. (1997, December). "Social" human-computer interaction. In *Human values and the design of computer technology* (pp. 191-199). Center for the Study of Language and Information.

[28] Koda, T., and Maes, P. (1996, November). Agents with faces: The effect of personification. In *Robot and Human Communication, 1996, 5th IEEE International Workshop on* (pp. 189-194).

[29] Takeuchi, A., and Naito, T. (1995, May). Situated facial displays: towards social interaction. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 450-455). ACM Press/ Addison-Wesley Publishing Co..

[30] Hinds, P. J., Roberts T. L., and Jones, H. (2004). Whose job is it anyway? A study of human-robot interaction in a collaborative task. Hum. Comput. Interact. 19: 151–181.

[31] Dautenhahn, K., Woods, S., Kaouri, C., Walters, M. L., Koay, K. L., and Werry, I. (2005). What is a robot companion-friend, assistant or butler? In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on* (pp. 1192-1197).

[32] Tapus, A., Maja, M., and Scassellatti, B. (2007). The grand challenges in socially assistive robotics. *IEEE Robotics and Automation Magazine*, *14*(1).

[33] Diegel, O., A. Badve, G. Bright, J. Potgieter, and S. Tlale (2002). Improved mechanum wheel design for omni-directional robots. Proc. 2002 Conf. Robotics and Automation, Aukland, 112-121.

[34] Katić D., and Vukobratović M. (2003). Survey of intelligent control techniques for humanoid robots. J. Intelligent and Robotic Systems, 37, 117-141.

[35] Zhou C., and Low, K. H. (2001). Combined use of ground learning model and active compliance to the motion control of walking robotic legs. Proc. 2001 IEEE Internat. Conf. Robotics and Automation, Seoul Korea. 3159-3164.

[36] Zhou, D., Low, K. H., and Zielinska, T. (2000). An efficient foot-force distribution algorithm for quadruped walking robots. Robotica Journal, vol. 18, pp. 403-413, Cambridge Univ. Press.

[37] Zielinska T., and Heng, J. (2002). Development of walking machine: mechanical design and control problems, Mechatronics, vol. 12, pp. 737-754.

[38] Hirai, K., M. Hirose, Haikawa, Y., and Takenaka, T. (1998). The development of Honda humanoid robot. Proc. 1998 IEEE Int. Conf. Robotics and Automation. Leuven, Belgium. 1321-1325.

[39] Gross, H., Schröter, C., Mueller, S., Volkhardt, M., Einhorn, E., Bley, A., Martin, Ch, Langner, T., and Merten, M. (2011). Progress in developing a socially assistive mobile home robot companion for the elderly with mild cognitive impairment. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on* (pp. 2430-2437).

[40] Horn, O., and Courcelle, A. (2004). Interpretation of ultrasonic readings for autonomous robot localization. J. Intelligent and Robotic Systems. 39: 265-285.

[41] Simpson, R. C. (2005). Smart wheelchairs: A literature review. *Journal of rehabilitation research and development*, *42*(4).

[42] Elfes A. (1987). Sonar-based real-world mapping and navigation. IEEE J. Robotics and Automation. 3(3); 249-265.

[43] Moravec, H. P. (1988). Sensor fusion in certainty grids for mobile robots. AI Magazine. vol. 9(2), 61-74.

[44] Kuipers, B., and Byun, Y-T. (1988). A robust qualitative method for spatial learning in unknown environments. Proc. 8th. Nat. Conf. AI AAAI-99. Menlo Park, Cambridge. AAAI Press/MIT Press.

[45] Kortenkamp, D., and Weymouth, T. (1994). Topological mapping for mobile robots using a combination of sonar and vision sensing. Proc. 12th Nat. Conf. AI. Menlo Park. Aaai Press/MIT Press. 979-984.

[46] Latombe, J. C. (1991). Robot Motion Planning, Kulwer Academic publishers, Boston, MA.

[47] Arsene, C. T. C., and Zalzala, A. M. S. (1999). Control of autonomous robots using fuzzy logic controllers tuned by genetic algorithms, Proc. of 1999 Congress on Evolutionary Computation pp. 428-435.

[48] Gallardo, D., and Colomina, O. (1998). A genetic algorithm for robust motion planning, Eleventh Int. Conf. on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems, Castellon, Spain, pp. 115-121.

[49] Durrant-Whyte, H., and Bailey, T. (2006). Simultaneous localization and mapping (SLAM): part i the essential algorithms. Robotics and Automation Magazine. vol. 13(2), pp. 99–110.

[50] Tarquini, F., De Felice, G., Fogliaroni, P., and Clementini, E. (2007). A qualitative model for visibility relations. KI 2007, Advances in Artificial Intelligence Lecture Notes in Computer Science. vol. 4667, pp. 510-513.

[51] Kuipers, B. (2000). The spatial semantic hierarchy. Artificial Intelligence. vol. 119, pp. 191-233

[52] Franz, M. O., Schölkopf, B., Mallot, H. A., and Bülthoff, H. H. (1998). Learning view graphs for robot navigation. Autonomous Robots. vol. 5, pp. 111-125.

[53] Remolina, E., and Kuipers, B. (2004). Towards a general theory of topological maps. Artificial Intelligence. vol. 152(1), pp. 47-104.

[54] Ulrich, I., and Borenstein, J. (2001). The GuideCane – Applying mobile robot technologies to assist the visually impaired. IEEE Trans Systems, Man and Cybernetics Part A, vol. 31(2), pp. 131-136.

[55] Burgard, W., Cremers, A. B., Fox, D., Hähnel, D., Lakemeyer, G., Schulz, S., Steiner, W., and Thrun, S. (1999). Experiences with an interactive museum tour-guide robot, Artificial Intelligence, 114(1-2): 3-55.

[56] Rodriguez-Losada, D., Matia, F., Jimenez, A., Galan, R., and Lacey, G. (2005, April). Implementing map based navigation in guido, the robotic smartwalker. In *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on* (pp. 3390-3395).

[57] Fox, D., Burgard, W., and Thrun, S. (1997). The dynamic window approach to collision avoidance. Robotics and Automation Magazine, IEEE vol. 4(1), pp. 23–33.

[58] Borenstein, J., and Koren, Y. (1991). The vector field histogram – fast obstacle avoidance for mobile robots. IEEE J. Robotics and Automation. 7(3): 278-288.

[59] Koren, Y., and Borenstein, J. (1991). Potential field methods and their inherent limitations for mobile robot navigation. In Int. Conference on Robotics and Automation, pp. 1398–1404, Sacramento, California.

[60] Simpson, R. C., Levine, S. P., Bell, D. A., Jaros, L. A., Koren Y., and Borenstein, J. (1998). Navchair: an assistive wheelchair navigation system with automatic adaptation. In Mittai V. A. et al. (eds.) Assistive Technology and AI, Berlin, Springer Verlag. 235-255.

[61] Khatib, O. (1986). Real-time obstacle avoidance for manipulators and mobile robots. Int. J. of Robotics Research, vol. 5(1), pp. 90–98.

[62] Simmons, R. G. (1996). The curvature velocity method for local obstacle avoidance. Proc. IEEE Int. Conf. on Robotics and Automation, vol. 4, pp. 2275-2282, 1996.

[63] Uribe, J. P., and Urzelai, J. (1998). Fuzzy controller for obstacle avoidance with a non-holonomous mobile robot. Mathware and Soft Computing, vol. 5, pp. 279-289.

[64] Wasson, G., Gunderson, J., Graves, S., and Felder, R. (2001, May). An assistive robotic agent for pedestrian mobility. In *Proceedings of the fifth international conference on Autonomous agents* (pp. 169-173).

[65] Huang, H. M., Pavek, K., Novak, B., Albus, J., and Messin, E. (2005). A framework for autonomy levels for unmanned systems (ALFUS). *Proceedings of AUVSI Unmanned Systems 2005*.

[66] Huang, H. M., Pavek, K., Albus, J., & Messina, E. (2005, May). Autonomy levels for unmanned systems (alfus) framework: An update. In Defense and Security (pp. 439-448). International Society for Optics and Photonics.

[67] Sheridan, T.B. (1992). Telerobotics, automation and human supervisory control. MIT Press.

[68] Sarter, N. (1998). Making coordination effortless and invisible: The exploration of automation management strategies and implementations. In *CBR Workshop on Human Interaction with Automated Systems*.

[69] Beer, J. M., Prakash, A., Mitzner, T. L., and Rogers, W. A. (2011). Understanding robot acceptance. School of Psychology, Georgia Institute of Technology Technical Report HFA-TR-1103.

[70] Sellner, B., Heger, F. W., Hiatt, L. M., Simmons, R., and Singh, S. (2006). Coordinated multiagent teams and sliding autonomy for large-scale assembly. *Proceedings of the IEEE*, *94*(7), 1425-1444.

[71] Goodrich, M. A., and Schultz, A. C. (2007). Human-robot interaction: a survey. *Foundations and trends in human-computer interaction*, *1*(3), 203-275.

[72] Scholtz, J. (2003, January). Theory and evaluation of human robot interactions. In *System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on*.

[73] Fong, T., Nourbakhsh, I., and Dautenhahn, K. (2003). A survey of socially interactive robots. *Robotics and autonomous systems*, *42*(3), 143-166.

[74] Barea, R., Boquete, L., Mazo, M., López, E., and Bergasa, L. M. (2000). EOG guidance of a wheelchair using neural networks. In *Pattern Recognition, 2000. Proceedings. 15th International Conference on* (vol. 4, pp. 668-671).

[75] Ferreira, A., Silva, R. L., Celeste, W. C., Bastos Filho, T. F., and Sarcinelli Filho, M. (2007, November). Human–machine interface based on muscular and brain signals applied to a robotic wheelchair. In *Journal of Physics: Conference Series* (vol. 90, no. 1, p. 012094). IOP Publishing.

[76] Katsura, S., and Ohnishi, K. (2004). Human cooperative wheelchair for haptic interaction based on dual compliance control. *Industrial Electronics, IEEE Transactions on*, *51*(1), 221-228.

[77] Kuno, Y., Shimada, N., and Shirai, Y. (2003). Look where you're going [robotic wheelchair]. *Robotics and Automation Magazine, IEEE*, *10*(1), 26-34.

[78] Moon, I., Lee, M., Ryu, J., and Mun, M. (2003). Intelligent robotic wheelchair with EMG-, gesture-, and voice-based interfaces. In *Intelligent Robots and Systems, 2003. (IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on* (vol. 4, pp. 3453-3458).

[79] Alami, R., Chatila, R., Fleury, S., Ghallab, M., and Ingrand, F. (1998). An architecture for autonomy, Int. J. Robotics Research, vol. 17(4), pp. 314-337.

[80] Simmons, R., and Apfelbaum, D. (1998). A task description language for robot control, Proc. Conf. on Intelligent.

[81] Rosenblatt, J. K. (1997). DAMN: A distributed architecture for mobile navigation, J. Expt. and Theoretical AI, vol. 9(2), pp. 339-360.

[82] Brooks, R. A. (1986). A robust layered control system for a mobile robot. *Robotics and Automation, IEEE Journal of*, *2*(1), 14-23.

[83] Nakashima, H., and Noda, I. (1998, July). Dynamic subsumption architecture for programming intelligent agents. In *Multi-Agent Systems, International Conference on* (pp. 190-190). IEEE Computer Society.

[84] Connell, J. H. (1992). SSS: a hybrid architecture applied to robot navigation, Proc. IEEE Conf. Robotics and Automation, pp. 2719-2724.

[85] Rosenblatt, J. K., and Payton, D. W. (1989). A fine-grained alternative to the subsumption architecture for mobile robot control, Int. Jt. Conf. on Neural Networks.

[86] Bonasso, P. et al. (1997). Three-tiered architecture for programming autonomous robots. J. Expt. Ther. Artificial Intelligence, vol. 9(2).

[87] Bernard, D., and PeAaall, B. (1997). Destined for autonomy: remote agent for the new millennium program, Proc. i-SAIRAS '97, Tokyo, Japan.

[88] Firby, R. J. (1987). An investigation into reactive planning in complex domains, Proc. Nat. Conf. AI, pp. 202-206, Seattle, WA.

[89] Mondada, F., Frani, E., and Ienne, P. (1994). Mobile robot miniaturisation: a tool for investigation in control architecture, Proc. of 3rd Int Symp. Experimental Robotics, Kyoto, Japan, Springer Verlag, pp. 501-513.

[90] Galindo, C., Gonzalez, J., and Fernandez-Madrigal, J. A. (2006). A control architecture for human-robot integration: application to a robotic wheelchair. *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on*, *36*(5), 1053-1067.

[91] Rialle, V., Duchene, F., Noury, N., Bajolle, L., and Demongeot, J. (2002). Health" smart" home: information technology for patients at home. *Telemedicine Journal and E-Health*, *8*(4), 395-409.

[92] Tang, P., and Venables, T. (2000). 'Smart' homes and telecare for independent living. *Journal of Telemedicine and Telecare*, *6*(1), 8-14.

[93] Yamazaki, T. (2006, November). Beyond the smart home. In *Hybrid Information Technology, 2006. ICHIT'06. International Conference on* (vol. 2, pp. 350-355)

[94] Aldrich, F. K. (2003). Smart homes: past, present and future. In *Inside the smart home* (pp. 17-39). Springer London.

[95] Cook, D. J., and Das, S. K. "Smart Environments: Technology, Protocols, and Applications," Wiley Inter-Science, 2005.

[96] Haigh, K. Z., and Yanco, H. (2002, July). Automation as caregiver: A survey of issues and technologies. In *AAAI-02 Workshop on Automation as Caregiver: The Role of Intelligent Technology in Elder Care* (pp. 39-53).

[97] Ghorbel, M., Segarra, M. T., Kerdreux, J., Keryell, R., Thepaut, A., and Mokhtari, M. (2004). Networking and communication in smart home for people with disabilities. In *Computers Helping People with Special Needs* (pp. 937-944). Springer Berlin Heidelberg.

[98] Zhang, D., Gu, T., and Wang, X. (2005). Enabling context-aware smart home with semantic web technologies. *International Journal of Human-friendly Welfare Robotic Systems*, *6*(4), 12-20.

[99] Baeg, M. H., Park, J. H., Koh, J., Park, K. W., and Baeg, M. H. (2007, October). Building a smart home environment for service robots based on RFID and sensor networks. In *Control, Automation and Systems, 2007. ICCAS'07. International Conference on* (pp. 1078-1082).

[100] Juels, A. (2006). RFID security and privacy: A research survey. *Selected Areas in Communications, IEEE Journal on*, *24*(2), 381-394.

[101] Ohkubo, M., Suzuki, K., and Kinoshita, S. (2005). RFID privacy issues and technical challenges. *Communications of the ACM*, *48*(9), 66-71.

[102] Wu, C. L., Liao, C. F., and Fu, L. C. (2007). Service-oriented smart-home architecture based on OSGi and mobile-agent technology. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, *37*(2), 193-205.

[103] Chapman, K., and McCartney, K. (2002). Smart homes for people with restricted mobility. *Property management*, *20*(2), 153-166.

[104] Demiris, G., and Hensel, B. K. (2008). Technologies for an aging society: a systematic review of "smart home" applications. *IMIA Yearbook Med Inform*, *3*, 33-40.

[105] Chan, M., Estève, D., Escriba, C., and Campo, E. (2008). A review of smart homes—Present state and future challenges. *Computer methods and programs in biomedicine*, *91*(1), 55-81.

[106] Gann, D., Barlow, J., and Venables, T. (1999). *Digital Futures: making homes smarter*. Coventry: Chartered Institute of Housing.

[107] Do, J. H., Jang, H., Jung, S. H., Jung, J., and Bien, Z. (2005, August). Soft remote control system in the intelligent sweet home. In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on* (pp. 3984-3989).

[108] Park, K. H., Bien, Z., Lee, J. J., Kim, B. K., Lim, J. T., Kim, J. O., Lee, H., Stefanov, D. H., Kim, D.-J., Jung, J.-W., Do, J.-H., Seo, K.-H., Kim, C. H., Song, W. G., and Lee, W. J. (2007). Robotic smart house to assist people with movement disabilities. *Autonomous Robots*, *22*(2), 183-198.

[109] Bailey, M., Chanler, A., Maxwell, B., Micire, M., Tsui, K., and Yanco, H. (2007). Development of vision-based navigation for a robotic wheelchair. In *Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on* (pp. 951-957).

[110] Simpson, R. C., LoPresti, E. F., and Cooper, R. A. (2008). How many people would benefit from a smart wheelchair? *Journal of Rehabilitation Research and Development*, *45*(1).

[111] Carlson, T., and Demiris, Y. (2010, May). Increasing robotic wheelchair safety with collaborative control: Evidence from secondary task experiments. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on* (pp. 5582-5587).

[112] Gonzalez, J., Muaeoz, A. J., Galindo, C., Fernandez-Madrigal, J. A., and Blanco, J. L. (2006, May). A description of the SENA robotic wheelchair. In *Electrotechnical Conference, 2006. MELECON 2006. IEEE Mediterranean* (pp. 437-440).

[113] Bourhis, G., Moumen, K., Pino, P., Rohmer, S., and Pruski, A. (1993, October). Assisted navigation for a powered wheelchair. In *Systems, Man and Cybernetics, 1993. 'Systems Engineering in the Service of Humans', Conference Proceedings, International Conference on* (pp. 553-558).

[114] Connell, J., and Viola, P. (1990). Cooperative control of a semi-autonomous mobile robot. In *Proceedings of the IEEE International Conference on Robotics and Automation* (vol. 2, pp. 1118-1121).

[115] Levine, S. P., Bell, D. A., Jaros, L. A., Simpson, R. C., Koren, Y., and Borenstein, J. (1999). The NavChair assistive wheelchair navigation system. *Rehabilitation Engineering, IEEE Transactions on*, *7*(4), 443-451.

[116] Borgolte, U., Hoyer, H., Bühler, C., Heck, H., and Hoelper, R. (1998). Architectural concepts of a semi-autonomous wheelchair. *Journal of Intelligent and Robotic Systems*, *22*(3-4), 233-253.

[117] Prassler, E., Scholz, J., and Fiorini, P. (1999). Navigating a robotic wheelchair in a railway station during rush hour. *The international journal of robotics research*, *18*(7), 711-727.

[118] Prassler, E., Scholz, J., and Fiorini, P. (2001). A robotics wheelchair for crowded public environment. *Robotics and Automation Magazine, IEEE*, *8*(1), 38-45.

[119] Katevas, N. I., Sgouros, N. M., Tzafestas, S. G., Papakonstantinou, G., Beattie, P., Bishop, J. M., Tsanakas, P., and Koutsouris, D. (1997). The autonomous mobile robot SENARIO: a sensor aided intelligent navigation system for powered wheelchairs. *Robotics and Automation Magazine, IEEE*, *4*(4), 60-70.

[120] Simpson, R., LoPresti, E., Hayashi, S., Nourbakhsh, I., and Miller, D. (2004). The smart wheelchair component system. *Journal of Rehabilitation Research and Development*, *41*.

[121] Simpson, R. C., Poirot, D., and Baxter, F. (2002). The Hephaestus smart wheelchair system. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *10*(2), 118-122.

[122] Miller, D. P., and Slack, M. G. (1995). Design and testing of a low-cost robotic wheelchair prototype. *Autonomous robots*, *2*(1), 77-88.

[123] Mazo, M. (2001). An integral system for assisted mobility. *IEEE Robotics and Automation Magazine*, 8(1), 46-56.

[124] Carlson, T., and Demiris, Y. (2012). Collaborative control for a robotic wheelchair: evaluation of performance, attention, and workload. *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on*, *42*(3), 876-888.

[125] Lawn, M. J., and Ishimatsu, T. (2003). Modeling of a stair-climbing wheelchair mechanism with high single-step capability. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *11*(3), 323-332.

[126] Odor, P., and Watson, M. (1994). Learning through smart wheelchairs. CALL Center, University of Edinburgh, Scotland, U.K., Tech. Rep., May 1994.

[127] Yanco, H. A. (1998). Wheelesley: A robotic wheelchair system: Indoor navigation and user interface. In *Assistive technology and artificial intelligence* (pp. 256-268). Springer Berlin Heidelberg.

[128] Uustal, H., and Minkel, J. L. (2004). Study of the Independence IBOT 3000 Mobility System: an innovative power mobility device, during use in community environments. *Archives of physical medicine and rehabilitation*, *85*(12), 2002-2010.

[129] Gomi, T., and Griffith, A. (1998). Developing intelligent wheelchairs for the handicapped. In *Assistive Technology and Artificial Intelligence* (pp. 150-178). Springer Berlin Heidelberg.

[130] Pires, G., and Nunes, U. (2002). A wheelchair steered through voice commands and assisted by a reactive fuzzy-logic controller. *Journal of Intelligent and Robotic Systems*, *34*(3), 301-314.

[131] Kobayashi, Y., Kinpara, Y., Shibusawa, T., and Kuno, Y. (2009, October). Robotic wheelchair based on observations of people using integrated sensors. In *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on* (pp. 2013-2018).

[132] Sato, Y., Arai, M., Suzuki, R., Kobayashi, Y., Kuno, Y., Yamazaki, K., and Yamazaki, A. (2013). A maneuverable robotic wheelchair able to move adaptively with a caregiver by considering the situation. In *RO-MAN, 2013 IEEE* (pp. 282-287). [

[133] Argyros, A., Georgiadis, P., Trahanias, P., and Tsakiris, D. (2002). Semi-autonomous navigation of a robotic wheelchair. *Journal of Intelligent and Robotic Systems*, *34*(3), 315-329.

[134] Martens, C., Ruchel, N., Lang, O., Ivlev, O., and Graser, A. (2001). A friend for assisting handicapped people. *Robotics and Automation Magazine, IEEE*, *8*(1), 57-65.

[135] Hillman, M., Hagan, K., Hagan, S., Jepson, J., and Orpwood, R. (2002). The Weston wheelchair mounted assistive robot-the design story. *Robotica*, *20*(2), 125-132.

[136] Prior, S. D. (1990). An electric wheelchair mounted robotic arm-a survey of potential users. *Journal of medical engineering and technology*, *14*(4), 143-154.

[137] Driessen, B. J. F., Evers, H. G., and V. Woerden, J. A. (2001). MANUS—a wheelchair-mounted rehabilitation robot. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *215*(3), 285-290.

[138] Kawamura, K., and Iskarous, M. (1994). Trends in service robots for the disabled and the elderly. In *Intelligent Robots and Systems' 94. 'Advanced Robotic Systems and the Real World', IROS'94. Proceedings of the IEEE/RSJ/GI International Conference on* (vol. 3, pp. 1647-1654).

[139] Rosier, J. C., Van Woerden, J. A., Van der Kolk, L. W., Driessen, B. J. F., Kwee, H. H., Duimel, J. J., Smits, J. J., Tuinhof de Moed, A. A., Honderd, G., and Bruyn, P. M. (1991). Rehabilitation robotics: The MANUS concept. In *Advanced Robotics, 1991. 'Robots in Unstructured Environments', 91 ICAR. Fifth International Conference on* (pp. 893-898).

[140] Kazi, Z., Salganicoff, M., Beitler, M. T., Chen, S., Chester, D., and Foulds, R. (1995). Multimodal user supervised interface and intelligent control (MUSIIC) for assistive robots. In *1995 IJCAI workshop on Developing AI Applications for the Disabled* (pp. 47-58).

[141] Danielsson, C., and Holmberg, L. (1994). Evaluation of the RAID workstation. In *ICORR'94 Proceedings of the International Conference on Rehabilitation Robotics, Wilmington, Delaware, June* (pp. 14-16).

[142] Van der Loos, H. M., Wagner, J. J., Smaby, N., Chang, K., Madrigal, O., Leifer, L. J., and Khatib, O. (1999). ProVAR assistive robot system architecture. In *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on* (vol. 1, pp. 741-746).

[143] Alqasemi, R. M., McCaffrey, E. J., Edwards, K. D., and Dubey, R. V. (2005,). Analysis, evaluation and development of wheelchair-mounted robotic arms. In *Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on* (pp. 469-472).

[144] Hoppenot, P., Colle, E., Aider, O. A., and Rybarczyk, Y. (2001). ARPH-assistant robot for handicapped people-a pluridisciplinary project. In *Robot and Human Interactive Communication, 2001. Proceedings. 10th IEEE International Workshop on* (pp. 624-629).

[145] Correal, R., Jardón, A., Martínez, S., Cabas, R., Giménez, A., and Balaguer, C. (2006, October). Human-Robot Coexistence in Robot-Aided Apartment. In *International Symposium on Automation and Robotics in Construction*.

[146] Tanaka, K., Kodani, Y., Oka, M., Nishimura, Y., Farida, F. A., and Mu, S. (2011). Meal assistance robot with ultrasonic motors. *International Journal of Applied Electromagnetics and Mechanics*, *36*(1), 177-181.

[147] Jardon, A., Giménez, A., Correal, R., Cabas, R., Martinez, S., and Balaguer, C. (2006). A portable light-weight climbing robot for personal assistance applications. *Industrial Robot: An International Journal*, *33*(4), 303-307.

[148] Jardón, A., Gil, Á. M., de la Peña, A. I., Monje, C. A., and Balaguer, C. (2011). Usability assessment of ASIBOT: a portable robot to aid patients with spinal cord injury. *Disability and Rehabilitation: Assistive Technology*, *6*(4), 320-330.

[149] Hegarty, J. (1991, April). Rehabilitation robotics: The user's perspective. In *Proceedings of the 2nd Cambridge Workshop on Rehabilitation Robotics*.

[150] Topping, M. J., and Smith, J. K. (1999). The development of Handy 1. A robotic system to assist the severely disabled. *Technology and Disability*, *10*(2), 95-105.

[151] Tachi, S., K. Tanie, Komiyama, K., and Abe, M. (1985). Electrocutaneous communication in a guide dog robot (MELDOG) IEEE Transactions on Biomedical Engineering, vol. B9ME-32(7), 461-469.

[152] Yelamarthi, K., Haas, D., Nielsen, D., and Mothersell, S. (2010). RFID and GPS integrated navigation system for the visually impaired. In *Circuits and Systems (MWSCAS), 2010 53rd IEEE International Midwest Symposium on* (pp. 1149-1152).

[153] Kulyukin, V., Gharpure, C., Nicholson, J., and Pavithran, S. (2004). RFID in robot-assisted indoor navigation for the visually impaired. In *Intelligent Robots and Systems, 2004. (IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on* (vol. 2, pp. 1979-1984).

[154] Kulyukin, V., Gharpure, C., Nicholson, J., and Osborne, G. (2006). Robot-assisted wayfinding for the visually impaired in structured indoor environments. *Autonomous Robots*, *21*(1), 29-41.

[155] Mori, H., and Kotani, S. (1998). Robotic travel aid for the blind: HARUNOBU-6. In *European Conference on Disability, Virtual Reality, and Assistive Technology*.

[156] Mori, H., and Kotani, S. (1998). A Robotic Travel Aid for the Blind. In *Robotics Research* (pp. 237-245). Springer London.

[157] Iwatsuka, K., Yamamoto, K., and Kato, K. (2004). Development of a guide dog system for the blind people with character recognition ability. In *Pattern Recognition, 2004. ICPR 2004. Proceedings of the 17th International Conference on* (vol. 1, pp. 453-456).

[158] Mori, H., Kotani S., and Kiyohiru N. 1998. HITOMI: design and development of a robotic travel aid. In Mittal VO et al. (eds.), Assistive Technology and AI, LNAI, pp. 221-234.

[159] Kulyukin, V., and Kutiyanawala, A. (2010). From ShopTalk to ShopMobile: vision-based barcode scanning with mobile phones for independent blind grocery shopping. In *Proceedings of the 2010 Rehabilitation Engineering and Assistive Technology Society of North America Conference (RESNA 2010), Las Vegas, NV*.

[160] Kutiyanawala, A., Kulyukin, V., and Nicholson, J. (2011). Teleassistance in accessible shopping for the blind. In *Proceedings of the 2011 International Conference on Internet Computing, July* (pp. 18-21).

[161] Lanigan, P. E., Paulos, A. M., Williams, A. W., Rossi, D., and Narasimhan, P. (2006, October). Trinetra: Assistive Technologies for Grocery Shopping for the Blind. In *ISWC* (pp. 147-148).

[162] López-de-Ipiña, D., Lorido, T., and López, U. (2011). Indoor navigation and product recognition for blind people assisted shopping. In *Ambient Assisted Living* (pp. 33-40). Springer Berlin Heidelberg.

[163] Nicholson, J., Kulyukin, V., and Coster, D. (2009). ShopTalk: independent blind shopping through verbal route directions and barcode scans. *The Open Rehabilitation Journal*, *2*, 11-23.

[164] Gharpure, C., Kulyukin, V., Jiang, M., and Kutiyanawala, A. (2006). Passive radio frequency exteroception in robot assisted shopping for the blind. In *Ubiquitous Intelligence and Computing* (pp. 51-60). Springer Berlin Heidelberg.

[165] Kulyukin, V., Gharpure, C., and Nicholson, J. (2005). Robocart: Toward robot-assisted navigation of grocery stores by the visually impaired. In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on* (pp. 2845-2850).

[166] Kulyukin, V., Gharpure, C., and Pentico, C. (2007). Robots as interfaces to haptic and locomotor spaces. In *Human-Robot Interaction (HRI), 2007 2nd ACM/IEEE International Conference on* (pp. 325-331).

[167] Epley, N., Waytz, A., and Cacioppo, J. T. (2007). On seeing human: a three-factor theory of anthropomorphism. *Psychological review*, *114*(4), 864-886.

[168] Dautenhahn, K. (2007). Socially intelligent robots: dimensions of human–robot interaction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1480), 679-704.

[169] Bartneck, C., and Forlizzi, J. (2004). A design-centred framework for social human-robot interaction. In *Proceedings of Ro-Man* (pp. 591-594).

[170] Feil-Seifer, D., and Mataric, M. J. (2005). Defining socially assistive robotics. In *Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on* (pp. 465-468).

[171] Scassellati, B., Admoni, H., and Mataric, M. (2012). Robots for use in autism research. *Annual Review of Biomedical Engineering*, *14*, 275-294.

[172] Feil-Seifer, D., Skinner, K., and Mataric, M. J. (2007). Benchmarks for evaluating socially assistive robotics. *Interaction Studies*, *8*(3), 423-439.

[173] Broekens, J., Heerink, M., and Rosendal, H. (2009). Assistive social robots in elderly care: a review. *Gerontechnology*, *8*(2), 94-103.

[174] Fujita, M. (2001). AIBO: Toward the era of digital creatures. *The International Journal of Robotics Research*, *20*(10), 781-794.

[175] Wada, K., and Shibata, T. (2007). Living with seal robots—its sociopsychological and physiological influences on the elderly at a care house. *Robotics, IEEE Transactions on*, *23*(5), 972-980.

[176] Wada, K., Shibata, T., Saito, T., and Tanie, K. (2004). Effects of robot-assisted activity for elderly people and nurses at a day service center. *Proceedings of the IEEE*, *92*(11), 1780-1788.

[177] Van Breemen, A., Yan, X., and Meerbeek, B. (2005). iCat: an animated user-interface robot with personality. In *Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems* (pp. 143-144).

[178] Allison, B., Nejat, G., and Kao, E. (2009). The design of an expressive humanlike socially assistive robot. *Journal of Mechanisms and Robotics*, *1*(1).

[179] Pineau, J., Montemerlo, M., Pollack, M., Roy, N., and Thrun, S. (2003). Towards robotic assistants in nursing homes: Challenges and results. *Robotics and Autonomous Systems*, *42*(3), 271-281.

[180] Pollack, M. E., Brown, L., Colbry, D., Orosz, C., Peintner, B., Ramakrishnan, S., Engberg, S., Matthews, J.T., Dunbar-Jacob, J., McCarthy, C.E., Thrun, S., Montemarlo, M., Pineau, J., and Roy, N. (2002). Pearl: A mobile robotic assistant for the elderly. In *AAAI workshop on automation as eldercare* (vol. 2002, pp. 85-91).

[181] Marti, P., Bacigalupo, M., Giusti, L., Mennecozzi, C., and Shibata, T. (2006). Socially assistive robotics in the treatment of behavioural and psychological symptoms of dementia. In *Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on* (pp. 483-488).

[182] Fasola, J., and Mataric, M. J. (2012). Using socially assistive human–robot interaction to motivate physical exercise for older adults. *Proceedings of the IEEE*, *100*(8), 2512-2526.

[183] Matarić, M., Tapus, A., Winstein, C., and Eriksson, J. (2009). Socially assistive robotics for stroke and mild TBI rehabilitation. *Advanced Technologies in Rehabilitation*, *145*, 249-262.

[184] Tapus, A., Ţăpuş, C., and Matarić, M. J. (2008). User—robot personality matching and assistive robot behavior adaptation for post-stroke rehabilitation therapy. *Intelligent Service Robotics*, *1*(2), 169-183.

[185] Libin, A., and Cohen-Mansfield, J. (2004). Therapeutic robocat for nursing home residents with dementia: preliminary inquiry. *American journal of Alzheimer's disease and other dementias*, *19*(2), 111-116.

[186] Mordoch, E., Osterreicher, A., Guse, L., Roger, K., and Thompson, G. (2013). Use of social commitment robots in the care of elderly people with dementia: A literature review. *Maturitas*, *74*(1), 14-20.

[187] Yomemitsu, S. Y. Higashi, T. Fujimoto, et al. (2002). Research for practical use of rehabilitation support equipment for severe dementia. Gerontology 2(1), 91.

[188] Robins, B., Dautenhahn, K., and Dubowski, J. (2006). Does appearance matter in the interaction of children with autism with a humanoid robot? *Interaction Studies*, *7*(3), 509-542.

[189] Diehl, J. J., Schmitt, L. M., Villano, M., and Crowell, C. R. (2012). The clinical use of robots for individuals with autism spectrum disorders: A critical review. *Research in Autism Spectrum Disorders*, *6*(1), 249-262.

[190] Gillesen, J. C. C., Barakova, E. I., Huskens, B. E. B. M., and Feijs, L. M. G. (2011). From training to robot behavior: Towards custom scenarios for robotics in training programs for ASD. In *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on* (pp. 1-7).

[191] Billard, A., Robins, B., Nadel, J., and Dautenhahn, K. (2007). Building Robota, a mini-humanoid robot for the rehabilitation of children with autism. *Assistive Technology*, *19*(1), 37-49.

[192] Barakova, E. I., and Lourens, T. (2010). Expressing and interpreting emotional movements in social games with robots. *Personal and ubiquitous computing*, *14*(5), 457-467.

[193] Shamsuddin, S., Yussof, H., Ismail, L., Hanapiah, F. A., Mohamed, S., Piah, H. A., and Ismarrubie Zahari, N. (2012). Initial response of autistic children in human-robot interaction therapy with humanoid robot NAO. In *Signal Processing and its Applications (CSPA), 2012 IEEE 8th International Colloquium on* (pp. 188-193).

[194] Dautenhahn, K., Nehaniv, C. L., Walters, M. L., Robins, B., Kose-Bagci, H., Mirza, N. A., and Blow, M. (2009). KASPAR–a minimally expressive humanoid robot for human–robot interaction research. *Applied Bionics and Biomechanics*, *6*(3-4), 369-397.

[195] Robins, B., Dautenhahn, K., Te Boekhorst, R., and Billard, A. (2005). Robotic assistants in therapy and education of children with autism: can a small humanoid robot help encourage social interaction skills? *Universal Access in the Information Society*, *4*(2), 105-120.

[196] Michaud, F., and Caron, S. (2000). Roball-an autonomous toy-rolling robot. In *In Proc. of the Workshop on Interactive Robotics and Entertainment*.

[197] Werry, I., and Dautenhahn, K. (1999). Applying mobile robot technology to the rehabilitation of

autistic children. In *In: Procs SIRS99, 7th Symp on Intelligent Robotic Systems*.

[198] Badii, A., Etxeberria, I., Huijnen, C., Maseda, M., Dittenberger, S., Hochgatterer, A., Thiemert, D., and Rigaud, A. S. (2009). CompanionAble: Graceful integration of mobile robot companion with a smart home environment. *Gerontechnology*, *8*(3), 181.

[199] Graf, B., Hans, M., and Schraft, R. D. (2004). Care-O-bot II — Development of a next generation robotic home assistant. *Autonomous robots*, *16*(2), 193-205.

[200] Graf, B., Reiser, U., Ha◎gele, M., Mauz, K., and Klein, P. (2009). Robotic home assistant Care-O-bot® 3-product vision and innovation platform. In *Advanced Robotics and its Social Impacts (ARSO), 2009 IEEE Workshop on* (pp. 139-144).

[201] Reiser, U., Connette, C. P., Fischer, J., Kubacki, J., Bubeck, A., Weisshardt, F., Jacobs, T., Partlitz, C, Hägele, M., and Verl, A. (2009). Care-O-bot® 3-creating a product vision for service robot applications by integrating design and technology. In *IROS* (vol. 9, pp. 1992-1998).

[202] Bubeck, A., Weisshardt, F., Sing, T., Reiser, U., Hagele, M., and Verl, A. (2012). Implementing best practices for systems integration and distributed software development in service robotics-the Care-O-bot® robot family. In *System Integration (SII), 2012 IEEE/SICE International Symposium on* (pp. 609-614).

[203] Deegan, P., Grupen, R., Hanson, A., Horrell, E., Ou, S., Riseman, E., Sen, S., Thibodeau, B., Williams, A., and Xie, D. (2008). Mobile manipulators for assisted living in residential settings. *Autonomous Robots*, *24*(2), 179-192.

[204] Lacey, G., and Dawson-Howe, K. M. (1998). The application of robotics to a mobility aid for the elderly blind. *Robotics and Autonomous Systems*, *23*(4), 245-252.

[205] Lacey, G., and MacNamara, S. (2000). User involvement in the design and evaluation of a smart mobility aid. *Journal of Rehabilitation Research and Development*, *37*(6).

[206] Dubowsky, S., Genot, F., Godding, S., Kozono, H., Skwersky, A., Yu, H., and Yu, L. S. (2000). PAMM-a robotic aid to the elderly for mobility assistance and monitoring: a "helping-hand" for the elderly. In *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on* (vol. 1, pp. 570-576).

[207] Spenko, M., Yu, H., and Dubowsky, S. (2006). Robotic personal aids for mobility and monitoring for the elderly. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *14*(3), 344-351.

[208] Nguyen, H., Anderson, C., Trevor, A., Jain, A., Xu, Z., and Kemp, C. C. (2008, March). El-e: An assistive robot that fetches objects from flat surfaces. In *Robotic helpers, int. conf. on human-robot interaction*.

[209] Dillon, A. (2001). "User acceptance of information technology, "in Karwowski, W. (ed.). Encyclopedia of Human Factors and Ergonomics. London: Taylor and Francis.

[210] Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, 319-340.

[211] Apostolos, M. K. (1985). "Exploring user acceptance of a robotic arm: a multidisciplinary case study (choreography, aesthetics, disabled)," Doctoral Dissertation.

[212] Ezer, N., Fisk, A. D., and Rogers, W. A. (2009). More than a servant: Self-reported willingness of younger and older adults to having a robot perform interactive and critical tasks in the home. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (vol. 53, No. 2, pp. 136-140). SAGE Publications.

[213] Ezer, N., Fisk, A. D., and Rogers, W. A. (2009). Attitudinal and intentional acceptance of domestic robots by younger and older adults. In *Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments* (pp. 39-48). Springer Berlin Heidelberg.

[214] Stafford, R. Q., Broadbent, E., Jayawardena, C., Unger, U., Kuo, I. H., Igic, A., Wong, R., Kerse, N., Watson, C., and MacDonald, B. A. (2010). Improved robot attitudes and emotions at a retirement home after meeting a robot. In *RO-MAN, 2010 IEEE* (pp. 82-87).

[215] Eyssel, F., Kuchenbrandt, D., Bobinger, S., de Ruiter, L., and Hegel, F. (2012). 'If you sound like me, you must be more human': on the interplay of robot and user features on human-robot acceptance and anthropomorphism. In *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction* (pp. 125-126).

[216] Shibata, T. (2004). An overview of human interactive robots for psychological enrichment. *Proceedings of the IEEE*, *92*(11), 1749-1758.

[217] Heerink, M., Krose, B., Evers, V., and Wielinga, B. (2006). The influence of a robot's social abilities on acceptance by elderly users. In *Robot and Human Interactive Communication, 2006. ROMAN 2006. The 15th IEEE International Symposium on* (pp. 521-526).

[218] Heerink, M., Kröse, B., Evers, V., and Wielinga, B. (2010). Relating conversational expressiveness to social presence and acceptance of an assistive social robot. *Virtual reality*, *14*(1), 77-84.

[219] Heerink, M., Kröse, B., Wielinga, B., and Evers, V. (2008). Enjoyment intention to use and actual use of a conversational robot by elderly people. In *Proceedings of the 3rd ACM/IEEE international conference on Human robot interaction* (pp. 113-120).

[220] Heerink, M., Ben, K., Evers, V., and Wielinga, B. (2008). The influence of social presence on accept-

ance of a companion robot by older people. *Journal of Physical Agents*, *2*(2), 33-40.

[221] Venkatesh, V., Morris, M. G., Davis, G. B., and Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS quarterly*.

[222] Goodhue, D. L., and Thompson, R. L. (1995). Task-technology fit and individual performance. *MIS quarterly*, 213-236.

[223] Nomura, T., Kanda, T., Suzuki, T., and Kato, K. (2004). Psychology in human-robot communication: An attempt through investigation of negative attitudes and anxiety toward robots. Proceedings of the 13th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN), (pp. 35-40).

[224] Nomura, T., Suzuki, T., Kanda, T., and Kato, K. (2006). Measurement of negative attitudes toward robots. Interaction Studies, 7(3), 437-454.

[225] Nomura, T., Suzuki, T., Kanda, T., and Kato, K. (2006). Measurement of anxiety toward robots. The 15th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN06), (pp. 372-377). Hatfield, UK.

[226] Heerink, M., Kröse, B., Evers, V., and Wielinga, B. (2010). Assessing acceptance of assistive social agent technology by older adults: the almere model. *International journal of social robotics*, *2*(4), 361-375.

[227] Hersh, M. A. (2013). Deafblind people, stigma and the use of communication and mobility assistive devices. *Technology and Disability*, *25*(4), 245-261.

[228] Goffman E. S., Notes on the management of spoiled identity. New York: Simon and Schuster; 1963.

[229] Livingston J. D., and Boyd, J. E. (2010). Correlates and consequences of internalised stigma for people living with mental illness: a systematic review and meta-analysis, Social Science and Medicine. *71*: 2150-2161.

[230] Weiss M. G., Ramakrishna J., Somma, D. (2006). Health-related stigma: rethinking concepts and interventions. Psychology, Health and Medicine. *11*(3): 277-287.

[231] Dengerink, J. E., and Porter, J. B. (1984). Children's attitudes towards peers wearing hearing aids. Language, Speech, and Hearing Services in the Schools. *47*: 205–209.

[232] Mulac A., Danhauer, J. L., and Johnson, C.E. (1983). Young adults' and peers' attitudes towards elderly hearing aid wearers. Australian Journal of Audiology. 5: 57–62.

[233] Hersh, M. A. (2014). Deafblind People, Stigma and the Use of Communication and Mobility Assistive Devices, Technology and Disability. 25(4): 245-261.

[234] Dunn, W. M., Foto, J., Hinojosa, B., Schell, L. K., Thomson, S., and Hertfelder, S. (1994). Uniform terminology for occupational-therapy - 3rd Edn. Am. J. of Occup. Therapy, vol. 48, no. 11, pp. 1047-1054.

[235] HEART, Line C Rehabilitation technology service delivery systems in Europe, Brussels, European Commission, 1995.