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Smart wheelchairs: A literature review

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Abstract — Several studies have shown that both children and adults benefit substantially from access to a means of independent mobility. While the needs of many individuals with disabilities can be satisfied with traditional manual or powered wheelchairs, a segment of the disabled community finds it difficult or impossible to use wheelchairs independently. To accommodate this population, researchers have used technologies originally developed for mobile robots to create "smart wheelchairs." Smart wheelchairs have been the subject of research since the early 1980s and have been developed on four continents. This article presents a summary of the current state of the art and directions for future research.

Key words: artificial intelligence, independent mobility, infrared range finder, laser range finder, machine vision, power wheelchairs, robotics, sonar, subsumption, voice control.

Abbreviations: ADL = activities of daily living, CALL = Communication Aids for Language and Learning, EOG = electro-oculographic, IR = infrared, LRF = laser range finder, MAid = Mobility Aid for elderly and disabled people, NLPR = National Laboratory of Pattern Recognition, OMNI = Office wheelchair with high Maneuverability and Navigational Intelligence, SPAM = Smart Power Assistance Module, SWCS = Smart Wheelchair Component System, VAHM = Véhicule Autonome pour Handicapé Moteur.

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INTRODUCTION

Several studies have shown that both children and adults benefit substantially from access to a means of independent mobility, including power wheelchairs, manual wheelchairs, scooters, and walkers [1-2]. Independent mobility increases vocational and educational opportunities, reduces dependence on caregivers and family members, and promotes feelings of self-reliance. For young children, independent mobility serves as the foundation for much early learning [1]. Nonambulatory children lack access to the wealth of stimuli afforded self-ambulating children. This lack of exploration and control often produces a cycle of deprivation and reduced motivation that leads to learned helplessness [3].

For adults, independent mobility is an important aspect of self-esteem and plays a pivotal role in "aging in place." For example, if older people find it increasingly difficult to walk or wheel themselves to the commode, they may do so less often or they may drink less fluid to reduce the frequency of urination. If they become unable to walk or wheel themselves to the commode and help is not routinely available in the home when needed, a move to a more enabling environment (e.g., assisted living) may be necessary. Mobility limitations are the leading cause of functional limitations among adults, with an estimated prevalence of 40 per 1,000 persons age 18 to 44 and 188 per 1,000 at age 85 and older [4]. Mobility difficulties are also strong predictors of activities of daily living (ADL) and instrumental ADL disabilities because of the need to move to accomplish many of these activities. In addition, impaired mobility often results in decreased opportunities to socialize, which leads to social isolation, anxiety, and depression. For example, 31 percent of persons with major mobility difficulties reported being frequently depressed or anxious, compared with only 4 percent of persons without mobility difficulties [5].

While the needs of many individuals with disabilities can be satisfied with traditional manual or powered wheelchairs, a segment of the disabled community finds it difficult or impossible to use wheelchairs independently. This population includes, but is not limited to, individuals with low vision, visual field reduction, spasticity, tremors, or cognitive deficits. These individuals often lack independent mobility and rely on a caregiver to push them in a manual wheelchair.

To accommodate this population, several researchers have used technologies originally developed for mobile robots to create "smart wheelchairs." A smart wheelchair typically consists of either a standard power wheelchair to which a computer and a collection of sensors have been added or a mobile robot base to which a seat has been attached. Smart wheelchairs have been designed that provide navigation assistance to the user in a number of different ways, such as assuring collision-free travel, aiding the performance of specific tasks (e.g., passing through doorways), and autonomously transporting the user between locations.

A recent survey indicated that clinicians have a strong desire for the services that a smart wheelchair can offer [6]. Significant survey results included:[1]

- Clinicians indicated that 9 to 10 percent of patients who receive power wheelchair training find it extremely difficult or impossible to use the wheelchair for ADL.
- When asked specifically about steering and maneuvering tasks, the percentage of patients who reported these tasks difficult or impossible jumped to 40 percent.
- Eighty-five percent of responding clinicians reported seeing some number of patients each year who cannot use a power wheelchair because they lack the requisite motor skills, strength, or visual acuity. Of these clinicians, 32 percent (27% of all respondents) reported seeing at least as many patients who cannot use a power wheelchair as who can.
- Nearly half of patients unable to control a power wheelchair by conventional methods would benefit from an automated navigation system according to the clinicians who treat them.

Smart wheelchairs have been the subject of research since the early 1980s and have been developed on four continents. This article presents a summary of the current state of the art and directions for future research. Because of the wealth of publications and projects, a single reference is provided for each system named[2] in the article, with an extensive bibliography provided in the **Appendix** (available online only at http://www.vard.org/jour/jourindx.htm).

DISTINGUISHING FACTORS OF SMART WHEELCHAIRS

Table 1 lists the smart wheelchairs that were identified by a search of the literature. Pictures of several of these smart wheelchairs are provided in **Figure**. As shown in the **Appendix Table** (available online only), the features of each smart wheelchair can be described in numerous ways and several of these are examined in more detail in the following:

Table 1.
Smart wheelchairs reported in literature.

Smart Wheelchair	PublicationDate Range	Description/URL
Automated-Guided Wheelchair NEC Corporation, Japan	1992	Follows tracks laid out with magnetic ferrite marker tape. Uses IR sensors to stop when obstacles detected in its path.
Autonomous Wheelchair Arizona State University, U.S.	1986	Uses machine vision to identify landmarks and center wheelchair in hallway.
CHARHM CDTA, Algeria	1996	Chair navigates autonomously to location in environment based on internal map and information from machine vision.
COACH French Atomic Energy Commission, France	1993	Provides obstacle avoidance and follows walls. Unclear how active operating mode is chosen.
CWA (Manual) National University of Singapore, Singapore	2002	Uses dead reckoning to keep wheelchair on prescribed path. User can leave path to avoid obstacles, and controls speed of wheelchair along path. Path can be defined with GUI or by walkthrough. Torque sensors in pushrims sense user input. Small motorized wheels apply force to regular manual wheelchair wheels. http://guppy.mpe.nus.edu.sg/~eburdet

CWA (Power) National University of Singapore, Singapore	2002	Uses dead reckoning to keep wheelchair on prescribed path. User can leave path to avoid obstacles, and controls speed of wheelchair. Path can be defined with GUI or by walkthrough. http://guppy.mpe.nus.edu.sg/~eburdet
CCPWNS University of Notre Dame, U.S.	1994-2000	User can automatically reproduce routes taught to system by manually driving wheelchair from starting point to goal point. Uses machine vision to identify landmarks in environment. No obstacle avoidance mode. http://www.nd.edu/~ame/facultystaff/Skaar%2CSteven.html#SkaarResearch3
Hephaestus TRAC Labs, U.S.	1999-2002	Provides obstacle avoidance. Compatible with multiple brands of wheelchairs and does not require any modifications to underlying power wheelchair.
INCH Yale University, U.S.	1989	Very early attempt that used small robot that drove like a wheelchair. Used sonar to avoid obstacles and drop-offs.
INRO FH Ravensburg-Weingarten, Germany	1998	Provides autonomous navigation (indoors and out) and wheelchair convoying.

Intelligent Wheelchair System Osaka University, Japan	1998-2003	Has two cameras, one facing toward user, second facing forward. User provides input to system with head gestures, interpreted by inward-facing camera. Outward-facing camera tracks targets and allows user to control wheelchair with gestures when out of wheelchair. Shares navigation with user (obstacle avoidance). Response to user input (facial gestures) adapts based on wheelchair's surroundings. Dead reckoning and a metric map first used to drive adaptation, then used sonar to identify environmental features. Provides target-tracking feature. When user looks straight ahead for short time, outward-facing camera identifies target and moves toward it. Outward-facing camera used to (1) identify pedestrians, (2) determine where user is looking, and (3) move chair in opposite direction to avoid collision. Developed second prototype that uses IR sensors instead of sonar. IR sensors follow moving caregiver. Chair automatically switches between modes (wall following, target tracking, obstacle avoidance) based on environment of wheelchair.

Intelligent Wheelchair University of Texas at Austin, U.S.	1998	Used as test bed for research into spatial representation and reasoning.
Luoson III National Chung Cheng University, Taiwan	1999-2000	Provides shared navigation assistance (obstacle avoidance) using force-feedback joystick. Can also follow autonomous service robot to destination.
MAid RIAKP, Germany	1998-2003	Has two operating modes: Narrow-Area Navigation (NAN) and Wide-Area Navigation (WAN). In NAN, system knows starting position and orientation and navigates to goal position and orientation. In WAN, system moves to goal destination but also identifies (and avoids) moving objects in environment. Later addition was the ability to follow moving objects.
Mister Ed IBM, U. S.	1990	Robot base with chair on top. Subsumption architecture for control. Groups of behaviors activated to achieve specific behaviors (door passage, wall following, target tracking).
Mr. HURI Yonsei University, Korea	2002-2003	Uses machine vision to identify facial gestures from user. Can also receive input from EMG (on neck) or voice commands. Uses sonar to avoid obstacles.
NavChair University of Michigan, U.S.	1993-2002	Prevents wheelchair from colliding with obstacles. Can automatically choose between multiple task-specific operating modes.

NLPR Robotized Wheelchair Chinese Academy of Sciences, China	2000	Uses machine vision to identify landmarks for localization. Offers several operating modes, including wall following, collision avoidance, and autonomous navigation to point on map.
OMNI University at Hagen, Germany	1995-1999	Omnidirectional wheelchair provides hierarchy of functionality: simple obstacle avoidance, task-specific operating mode (wall following, door passage), and autonomous navigation. Operating modes implemented and mechanism of mode switching unclear. http://prt.fernuni-hagen.de/pro/omni/omni-eng.html
Orpheus National Technical University of Athens, Greece	1996-2002	Either navigates autonomously to position or provides obstacle avoidance while user navigates.
Phaeton Northeastern University, U.S.	1998	User controls wheelchair through deictic interface; user chooses object from video screen that wheelchair then uses as target. http://faculty.olin.edu/~jcrisman/CV%20&%20Bio/NU%20Site/projects/phaeton/index.html
RobChair University of Coimbra, Portugal	1997-2002	Provides local obstacle-avoidance assistance. User manually switches between general collision-avoidance and wall-following modes. http://www.isr.uc.pt/~gpires/frame_index.html?/~gpires/robchair/robchair.html
Smart Wheelchair	**Publication Date Range**	**Description/URL**

Robotic Wheelchair FORTH, Greece	1996-2002	Uses panoramic (360°) camera for computer vision. Has two operating modes: obstacle avoidance and person tracking. http://www.ics.forth.gr/~tsakiris/Projects/grants.html
Rolland University of Bremen, Germany	1997-2002	Kollman et al. [1] used Rolland as test bed for autonomous navigation research. Wheelchair used dead reckoning and landmark detection (via machine vision) for self-localization. Used sonar, IR, and bump sensors to avoid collisions. Autonomously navigated between positions on map. Buhlmeier et al. [2-3] used system as test bed for neural network-based motion control. Röfer [4-8] implemented several operating modes (wall following, door passage) and ability to play back taught routes. Landmarks in environment would trigger changes in operating mode. Second prototype developed by Röfer and Lankenau [9-14] only used sonar; had more sophisticated obstacle avoidance algorithm. System has three operating modes (turn-in-place, wall following, and trajectory playback) and same landmark-based mode-switching algorithm. Second prototype uses sonar and dead reckoning to trigger mode changes. User teaches trajectory using turn-in-place and wall-following behaviors, and trajectory can then be repeated. User can also

		drive wheelchair, with wheelchair modifying its velocity to avoid obstacles. Automatic mode transitions triggered by obstacle density. Röfer [4-8] used second Rolland prototype as basis for research in using laser range finder to dynamically generate metric maps. http://www.informatik.uni-bremen.de/rolland/index_e.htm
SENARIO TIDE, Finland	1995-1998	Provides shared-control navigation (obstacle avoidance) and autonomous navigation based on internal map. Uses neural networks for localization, and distributed control architecture. http://147.102.33.1/mobinet/mobnews1.htm
Siamo University of Alcala, Spain	1999-2003	Used as a test bed for various input methods (voice, face/head gestures, EOG). Provides obstacle avoidance. Uses machine vision to interpret user's gaze for control of wheelchair and to identify landmarks. Uses both laser and IR to detect drop-offs. Uses modular architecture based on commercially available building automation hardware. Allows chair to interact wirelessly with hardware nodes in environment.
SIRIUS University of Seville, Spain	2001-2002	Provides obstacle avoidance and can "rewind" recorded trajectory to exit tight location (bathroom).

Smart Alec Stanford University, U.S.	1990	Sonar used to detect user's head position. User can select from operating modes: collision avoidance, target tracking, and wall following.
Smart Wheelchair CALL Center, UK	1996-2002	Used as mobility training aid. Follows lines and backs up when it collides with an obstacle. http://callcentre.education.ed.ac.uk/Smart_WheelCh/smart_wheelch.html
Smart Wheelchair Chinese University of Hong Kong, China	2002	Uses neural network to map sensor readings to control actions to play back taught routes.
Smart Wheelchair Kanazawa University, Japan	2000	Determines its location by time-of-flight calculations from ultrasonic beacons. Uses location information to provide autonomous navigation. Prototype does not provide obstacle avoidance. http://as.ms.t.kanazawa-u.ac.jp/as-e.html
Smart Wheelchair Toyohashi University, Japan	2001	Omnidirectional wheelchair that uses force-feedback joystick to prevent user from colliding with obstacles.
Smart Wheelchair University of Ancona, Italy	1998-2000	Either stops when obstacles detected or attempts to steer around them.
Smart Wheelchair University of Plymouth, UK	1998	Used controller based on neural networks to trace predefined paths autonomously within art gallery for 1 mo. Used machine vision for localization.

Smart Wheelchair University of Portsmouth, UK	1994-2000	Demonstrated ability to steer wheelchair through doorway based on information from sonar.
SmartChair University of Pennsylvania, U.S.	2002-2003	Provides several modes of operation, including "travel to target" mode that uses a deictic interface, hallway navigation, door passage, three-point-turn, and collision avoidance. Machine vision and laser range finder fused to calculate depth information.
SPAM AT Sciences, U.S.	2003-2004	Based on manual wheelchair. Prevents wheelchair from colliding with obstacles. Is compatible with multiple brands of wheelchairs and does not require any modifications to underlying power wheelchair.
SWCS AT Sciences, U.S.	2003-2004	Prevents wheelchair from colliding with obstacles. Is compatible with multiple brands of wheelchairs and does not require any modifications to underlying power wheelchair.
TAO Applied AI Systems, Inc., Canada	1996-1998	Series of prototypes based on power wheelchairs. Requires minimal modifications to underlying wheelchair. Uses IR and machine vision to detect obstacles. Uses subsumption architecture, from which several behaviors emerge, including collision avoidance, door passage, wall following, and autonomous navigation. http://www.aai.ca/robots/tao_7.html

TetraNauta University of Seville, Spain	1998-2004	Designed as system that can be added on to multiple makes/models of wheelchairs. Provides autonomous navigation by following landmarks (floor markings and radio beacons) in environment.
TinMan KIPR, U. S.	1994-1999	Series of smart wheelchair prototypes based on power wheelchairs. Original prototype used mechanical interface to wheelchair joystick, but subsequent prototypes integrated into control electronics of wheelchairs. Provides collision avoidance and autonomous navigation. http://www.kipr.org/robots/tm.html

Smart Wheelchair	Publication Date Range	Description/URL
VAHM Universite de Metz, France	1992-2004	First VAHM built on modified mobile robot base. Three-level control architecture provided autonomous navigation (based on internal map) or two semiautonomous behaviors (wall following, obstacle avoidance). Mode decisions made manually. VAHM uses multiple representations of environment (topological, metric) and IR beacons for path planning. Second VAHM based on modified power wheelchair. Uses same three-level control architecture, mapping schemes, and IR beacons. VAHM provides autonomous navigation and semiautonomous behaviors and mode decisions are made manually. http://www.lasc.

		univ-metz.fr/rubrique.php3?id_rubrique=7
Voice-cum-Auto Steer Wheelchair CEERI, India	1999-2000	Wheelchair can autonomously travel to destination based on internal map or by following tape tracks on floor. IR sensors used to prevent collisions and follow tape tracks.
WAD Project Bochum University, Germany	2002	Either navigates autonomously to position or provides obstacle avoidance while user navigates.
Waston NAIST, Japan	2001-2003	Uses machine vision to interpret user's gaze for control of wheelchair. Uses lasers to identify obstacles.
Wheelesely MIT, U.S.	1995-2002	Uses machine vision for obstacle detection, which allows wheelchair to travel safely outdoors. Automatically switches between indoor and outdoor navigation modes. Has been used as test bed for EOG-based input. Provides collision avoidance and keeps wheelchair on path/ sidewalk when outdoors.

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AI = artificial intelligence, CALL = Communication Aids for Language and Learning, CCPWNS = Computer-Controlled Power Wheelchair Navigation System, CDTA = Advanced Technology Development Center, CEERI = Central Electronics Engineering Research Institute, CHARHM = Chaise Roulante Autonome pour Handicapé Moteur, COACH = Computer Assisted Wheelchair for Handicapped People, CWA = Collaborative Wheelchair Assistant, EMG = electromyography, EOG = electro-oculographic, FH = Fachhochschule, FORTH = Foundation for Research and Technology, GUI = graphical user interface, IBM = International Business Machines, INCH = Intelligent Wheelchair, INRO = Intelligenter Rollstuhl, IR = infrared (range finder), KIPR = KISS Institute for Practical Robotics, MAid = Mobility Aid for elderly and disabled people, MIT = Massachusetts Institute of Technology, NAIST = NARA Institute of Science and Technology, NLPR = National Laboratory of Pattern Recognition, OMNI = Office Wheelchair with High Manoeuvrability and Navigational Intelligence, RIAKP = Research Institute for Applied Knowledge Processing, SPAM = Smart Power Assistance Module, SWCS = Smart Wheelchair Component System, TIDE = Technology Initiative for Disabled and Elderly, TRAC = Texas Robotics and Automation Center, URL = uniform resource locator, VAHM = Véhicule Autonome pour Handicapé Moteur, WAD = Wheelchair Attractor Dynamics.


NavChair
Hephaestus
SWCS
SPAM

Figure 1.
Gallery of smart wheelchairs. SWCS = Smart Wheelchair Component System, SPAM = Smart Power Assistance Module.

Form Factor

One obvious way to classify smart wheelchairs is form factor. Early smart wheelchairs (e.g., Véhicule Autonome pour Handicapé Moteur [VAHM] [7], Mister Ed [8]) were actually mobile robots to which seats were added. The majority of smart wheelchairs that have been developed to date have been based on heavily modified, commercially available power wheelchairs (e.g., NavChair [9], Office wheelchair with high Maneuverability and Navigational Intelligence [OMNI] [10], Mobility Aid for elderly and disabled people [MAid] [11], SENARIO [12]); a smaller number of smart wheelchairs (e.g., Smart Wheelchair Component System [SWCS] [13], Smart Power Assistance Module [SPAM] [14], Hephaestus [15], TinMan [16], Siamo [17]) have been designed as "add-on" units that can be attached to and removed from the underlying power wheelchair.

There are several advantages to integrating the smart wheelchair technology into the underlying power wheelchair. Perhaps most important, the user's input can be fed directly into the processor to the wheelchair's motors, bypassing the manufacturer's proprietary control electronics. This eliminates the need to "reverse engineer" the protocol that the wheelchair manufacturer uses to communicate between the joystick and the motor controller. An additional benefit of tight integration is the ability to add optical encoders to the wheels, which allows the wheelchair to track its velocity. Systems designed as add-on units, on the other hand, must connect to the underlying wheelchair through the limited interface options provided by the wheelchair manufacturer. Early add-on units (e.g., Hephaestus) were able to take advantage of analog connections between the joystick and the motor controller. It was relatively simple to intercept the continuous stream of voltages generated by the joystick, modify that stream, and pass it on to the wheelchair's motor controller. More recent add-on units have to contend with proprietary digital control buses, which greatly complicate the task of interfacing with the wheelchair. The SWCS, for example, must take different approaches to interfacing with different brands of wheelchairs. For wheelchair manufacturers that use Penny + Giles electronics (including Permobil, Sunrise Medical, and Jazzy), the SWCS connects to the Omni + module (Permobil and Jazzy) or QTronix Universal Specialty Controls Module (Sunrise Medical). For Invacare wheelchairs, the SWCS uses the switch joystick interface provided by the digital drive box.

The promised advantage of the add-on unit approach is that a consumer will be able to buy the system once and transfer it to multiple chairs over their lifetime. This is particularly important for children, who may go through several wheelchairs in a short period of time as their bodies grow. The add-on approach also lends itself more readily to flexible configurations of sensors and input devices based on each individual user's needs.

Currently, only two smart wheelchairs are based on manual wheelchairs. The Collaborative Wheelchair Assistant (manual) [18] controls the direction of a manual wheelchair with small motorized wheels that are placed in contact with the wheelchair's rear tires to transfer torque to the rear wheels. The SPAM uses pushrim-activated, power-assist wheelchair hubs in place of traditional rear wheels [19-20].

Input Methods

Smart wheelchairs have been used to explore a variety of alternatives to the more "traditional" input methods associated with power wheelchairs (e.g., joysticks, pneumatic switches). Voice recognition has often been used for smart wheelchairs (e.g., NavChair, SENARIO, TetraNauta [21]) because of the low cost and widespread availability of commercial voice recognition hardware and software. More exotic input methods that have been implemented include detection of the wheelchair user's sight path (i.e., where the user is looking) through electro-oculographic (EOG) activity (e.g., Wheelesely [22], Siamo) or the use of machine vision to calculate the position and orientation of the wheelchair user's head (e.g., Osaka University [23], Watson [24]).

Smart wheelchairs are excellent test beds for novel input methods because, unlike standard wheelchairs, smart wheelchairs have an onboard computer with which input sensors can interface. More importantly, the obstacle avoidance provided by smart wheelchairs provides a safety net for input methods that are inaccurate or have limited bandwidth. Voice control, for example, has proven very difficult to implement successfully on standard wheelchairs [25-28]. However, on the NavChair [29], the obstacle avoidance capabilities built into the control software protect the user from the consequences of unrecognized (or misrecognized) voice commands. The software also "fills in" small, rapid navigation commands that are much easier with a high-bandwidth input device like a joystick.

Sensors

To avoid obstacles, smart wheelchairs need sensors to perceive their surroundings. By far, the sensor most frequently used by smart wheelchairs is the ultrasonic acoustic range finder (i.e., sonar). Sonar sensors are very accurate when the sound wave emitted by the sensor strikes an object at a right angle or head on. As the angle of incidence increases, however, the likelihood that the sound wave will not reflect back toward the sensor increases. This effect is more pronounced if the object is smooth or sound absorbent. Sonar sensors are also susceptible to "cross talk," which happens when the signal generated by one sensor produces an echo that is received by a different sensor.

Another frequently used sensor is the infrared (IR) range finder. IR sensors emit light, rather than sound, and can be fooled by dark or light absorbent material rather than sound absorbent material. IR sensors also have difficulty with transparent or refractive surfaces. Despite their limitations, however, sonar and IR sensors are often used because they are small, inexpensive, and well understood.

Neither sonar nor IR sensors are particularly well suited to identifying drop-offs, such as stairs, curbs, or potholes. It is not uncommon for floors to be dark and smooth, which means that both sonar and IR sensors would need to be facing almost straight down toward the ground to receive an echo. In this case, the smart wheelchair would not have warning in enough time to stop.

More accurate obstacle and drop-off detection is possible with laser range finders (LRFs), which provide a 180°, two-dimensional scan within the plane of the obstacles in the environment. Examples of smart wheelchairs that use a LRF include Rolland [30], MAid, and SENARIO. Unfortunately, LRFs are expensive, are large, and consume lots of power, which makes the task of mounting enough of them on a smart wheelchair to provide complete coverage difficult.

Another option is a "laser striper," which consists of a laser emitter and a charge-coupled device camera. The image of the laser stripe returned by the camera can be used to calculate distances to obstacles and drop-offs based on discontinuities in the stripe. A laser striper is less expensive than a LRF, but can return false readings when the stripe falls on glass or a dark surface. To date, the laser striper system has not been used with a smart wheelchair.

A significant obstacle to bringing intelligent mobility aids to market is the need for sensors that are accurate, inexpensive, small, lightweight, and impervious to environmental conditions (e.g., lighting, precipitation, temperature): they also have to have low power requirements. Because no single sensor exists that meets these needs, many smart wheelchairs (e.g., VAHM, TAO [31], OMNI, Rolland) fuse information from multiple sensors to locate obstacles. In this way, the limitations of one sensor can be compensated for by other sensors. For this reason, sonar and IR sensors are frequently used in combination. When other sensors fail, the last line of defense is often the bump sensor that is triggered when a smart wheelchair comes in contact with an obstacle.

Perhaps the most promising sensor technology is machine vision. Cameras are much smaller than LRFs and, thus, much easier to mount in multiple locations on a wheelchair. Cameras can also provide much greater sensor coverage. The cost of machine vision hardware has fallen significantly-what used to require special cameras and frame grabbers can now be accomplished with a $20 universal serial bus web camera-and machine vision software continues to improve, which makes successful implementation of a smart wheelchair based on computer vision increasingly likely. Smart wheelchairs already use computer vision for landmark detection (e.g., Rolland, MAid, Computer-Controlled Power Wheelchair Navigation System [32]), and as a means of head- and eye-tracking for wheelchair control (e.g., Watson, Mr. HURI [33], Siamo).

Control Software

Investigators have taken a variety of approaches to implementing control software for smart wheelchairs based on the functions supported by the smart wheelchair and the sensors it uses. The University of Plymouth [34] and the Chinese University of Hong Kong [35], for example, both developed smart wheelchairs that use neural networks to reproduce pretaught routes. The NavChair, on the other hand, uses an obstacle density histogram to combine information from its sonar sensors with joystick input from the user, and the SWCS and SPAM use rule-based approaches.

Several smart wheelchairs use subsumption control architectures [36], in which primitive "behaviors" are coupled to produce more sophisticated emergent behavior (e.g., TAO, Mister Ed, National Laboratory of Pattern Recognition [NLPR] Robotized Wheelchair [37]). Reactive control methods, like subsumption, are occasionally used as the lowest layer of a multilayered control architecture. The reactive control layer provides sense-react behaviors that interact directly with the underlying hardware, while the upper layers of the architecture provide deliberative reasoning and control. Examples of smart wheelchairs that use a multilayered control architecture include VAHM (which uses a subsumption control approach at its lowest level), OMNI, and Rolland.

Operating Modes

Some smart wheelchairs (e.g., TetraNauta, Kanazawa University [38]) operate in a manner very similar to autonomous robots; the user gives the system a final destination and supervises as the smart wheelchair plans and executes a path to the target location. To reach their destination, these systems typically require either a complete map of the area through which they must navigate or some sort of modification to their environment (e.g., tape tracks placed on the floor or markers placed on the walls); they are usually unable to compensate for unplanned obstacles or travel in unknown areas. Smart wheelchairs in this category are most appropriate for users who (1) lack the ability to plan or execute a path to a destination and (2) spend the majority of their time within the same controlled environment.

Other smart wheelchairs confine their assistance to collision avoidance and leave the majority of planning and navigation duties to the user (e.g., NavChair, TinMan). These systems do not normally require prior knowledge of an area or any specific alterations to the environment. They do, however, require more planning and continuous effort on the part of the user and are only appropriate for users who can effectively plan and execute a path to a destination. A final group of smart wheelchairs offers both autonomous and semiautonomous navigation (e.g., VAHM, SENARIO, SmartChair [39]).

Within the group of smart wheelchairs that offer semiautonomous navigation assistance, a subset offer multiple behaviors, each designed for a specific set of tasks and input methods. For example, the NavChair offers three distinct operating modes for (1) traversing a room while avoiding obstacles, (2) passing through doorways, and (3) following a wall down a hallway. Other smart wheelchairs that offer task specific behaviors include Wheelesely, Mister Ed, OMNI, and Rolland. Smart wheelchairs in this subset are able to accommodate a wider range of needs and abilities, but present the added requirement of the user selecting the most appropriate configuration for a given task.

The responsibility for selecting the most appropriate operating mode can be performed by the user (manual adaptation) or the smart wheelchair (automatic adaptation). The TinMan smart wheelchair provides an example of manual adaptation. Users can change the setting of a dial to specify the amount of obstacle avoidance assistance provided by the chair. The NavChair and the TAO systems, on the other hand, use automatic adaptation. The NavChair uses probabilistic reasoning techniques to combine information from the sonar sensors and a topological map to make adaptation decisions, while the TAO system uses a subsumptive reasoning system to allow the most appropriate behavior to emerge from a collection of potential behaviors.

Table 2 lists the operating modes that have been described in the literature. The operating mode used most frequently is a general-purpose collision-avoidance mode. Smart wheelchairs also have task-specific modes, such as wall following (e.g., NavChair, VAHM, Siamo), door passage (e.g., Rolland, SmartChair, Mister Ed), and docking (e.g., OMNI, Siamo), because these behaviors have specific performance criteria that are often at odds with the behavior expected from a more general collision-avoidance mode. For example, a general collision-avoidance mode typically provides the fastest possible rate of travel and the most control to the user, but also enforces the greatest separation from obstacles. A door-passage mode, on the other hand, must allow the wheelchair to come close to objects to pass through narrow doorframes, at the expense of travel speed and user control.

Table 2.
Operating modes reported in smart wheelchair literature.

Operating Mode	Description
Autonomous Navigation with Obstacle Avoidance	Smart wheelchair travels from its current location to given destination based on internal map. Some smart wheelchairs do not perform obstacle avoidance while navigating autonomously.
Collision Avoidance	Wheelchair operator is responsible for planning path to destination. Smart wheelchair either avoids or stops in front of obstacles. Speed is often increased, along with minimum obstacle clearance.

Wall Following	Smart wheelchair maintains fixed distance from wall.
Door Passage	Smart wheelchair facilitates traversing doorway. Speed is reduced to allow wheelchair to approach closer obstacles.
Docking	Smart wheelchair allows close approach to an object.
Trajectory Playback	Smart wheelchair reproduces programmed path. Paths are typically programmed by demonstration.
Reverse Trajectory	Smart wheelchair can "undo" its actions to return to starting position.
Target Tracking	Smart wheelchair can track and navigate to stationary or moving object.
Line Following	Smart wheelchair can follow track that is physically marked in environment. Some can plan paths that involve intersection of multiple paths.
Turn Around	Smart wheelchair can reverse direction, either turning in place or executing three-point turn.
Bump and Backup	Smart wheelchair stops, then backs up when contact switch is activated.

Internal Mapping and Landmarks

Smart wheelchairs that navigate autonomously to a destination often do so with an internal map. The map can encode distance (in which case it is referred to as a metric map) or can be limited to specifying the connections between locations without any distance information (i.e., a topological map). There are, of course, other approaches to autonomous navigation that do not require an internal map, such as following tracks laid on the floor (e.g., Automated-Guided Wheelchair [40]).

A significant problem with the use of an internal map is unambiguously determining where the wheelchair is located on the map. A small number of smart wheelchairs (e.g., TAO, NLPR Robotized Wheelchair) use machine vision to identify naturally occurring landmarks in the environment, but the majority of smart wheelchairs create "artificial" landmarks that can be easily identified and linked with a unique location. Most smart wheelchairs use machine vision to locate artificial landmarks, but other smart wheelchairs have used radio beacons (e.g., MAid, TetraNauta).

Several smart wheelchairs also use a "local" map that moves with the wheelchair (e.g., NavChair, Rolland, SENARIO). This map is often referred to as an "occupancy or certainty grid" [41] and stores the location of obstacles in the wheelchair's immediate vicinity. Occupancy grids are used as the basis for many obstacle avoidance methods.

Commercialization

Despite a long history of research in smart wheelchairs, very few smart wheelchairs are currently on the market (**Table 3**). Two North American companies, Applied AI Systems, Inc., Ontario, Canada, and ActivMedia, Amherst, New Hamshire, sell smart wheelchair prototypes for use by researchers, but neither system is intended for use outside of a research lab. The Communication Aids for Language and Learning (CALL) Center smart wheelchair is sold in Europe by Smile Rehab, Ltd., (Berkshire, United Kingdom) as the "Smart Wheelchair." The "Smart Box," which is also sold by Smile Rehab, is compatible with wheelchairs that use either Penny + Giles or dynamic control electronics and includes bump sensors (but not sonar sensors) and the ability to follow tape tracks on the floor.

Table 3.
Comparison of commercially available smart wheelchairs.

Specifications	Smart Wheelchair	Smart Box	TAO-7	Wheelchair Pathfinder	Robotic Chariot
Distributor	Smile Rehab, Ltd.	Smile Rehab, Ltd.	Applied AI Systems, Inc.	Nurion Industries	ActivMedia
Price	$14,200	$5,000	$37,400	$4,500	$36,490
Sensors	Sonar, bump sensors, line detection	Bump sensors, line detection	Sonar, infrared range finders, computer vision	Sonar, laser range finder	Laser range finder, shaft encoders, bump sensors, GPS,* computer vision*

Operating Modes	Bump and stop, bump and backup, bump and turn, line following	Bump and stop, bump and backup, bump and turn, line following	Wander randomly, shared navigation, autonomous navigation	Vibrate when obstacle or drop-off detected. No active control of wheelchair.	Wander randomly, shared navigation, autonomous navigation
Wheelchair Included	Yes	No	Yes	No	Yes
User Population	Children	Children or adults	Researchers	Children or adults with visual impairments	Researchers
*optional		GPS = global positioning system		AI = artificial intelligence	

Limited commercial availability has resulted in limited clinical impact as well. The CALL Center has, by far, the most clinical experience in using smart wheelchairs [42]. The CALL Center uses a standard power wheelchair, equipped with bump sensors and line tracking sensors, as an instructional tool for children learning to operate a power wheelchair. Clients use the smart wheelchair to progress along a continuum of skills until they (1) reach the limit of their control potential (at which point they continue to use the smart wheelchair as a mobility aid) or (2) reach the point where they are fully independent. Other reported uses of smart wheelchairs within training programs include the Sensing Collision Avoidance Detector wheelchair [43] and the Robotic Trainer [44].

FUTURE RESEARCH

Smart wheelchairs will remain fertile ground for technological research for many years to come. Smart wheelchairs are excellent test beds for sensor research, particularly machine vision. Smart wheelchairs also provide an opportunity to study human-robot interaction, adaptive or shared control, and novel input methods, such as voice control, EOG, and eye-tracking. Furthermore, smart wheelchairs will continue to serve as test beds for robot control architectures.

While there has been a significant amount of effort devoted to the development of smart wheelchairs, scant attention has been paid to evaluating their performance. As shown in the **Appendix Table** (available online only), very few smart wheelchair researchers have involved people with disabilities in their evaluation activities. Furthermore, no smart wheelchair has been subjected to a rigorous, controlled evaluation that involves extended use in real-world settings. Conducting user trials with smart wheelchairs is difficult for several reasons. Some wheelchair users do not show any immediate improvement in navigation skills (measured in terms of average velocity and number of collisions) when using a smart wheelchair on a closed course in a laboratory setting. This could be because the smart wheelchair does not work very well or the wheelchair user was already so proficient that little improvement was possible. Users who have the potential to show large performance gains, on the other hand, often have little or no experience with independent mobility and may need a significant amount of training before they are ready to participate in valid user trials.

The primary obstacle to conducting long-term studies is the prohibitive hardware costs associated with constructing enough smart wheelchairs. Long-term studies are necessary, however, because the actual effects of using a smart wheelchair for an extended period of time are unknown. Some investigators (e.g., The CALL Center) have intended their smart wheelchair to be used as a means of developing the necessary skills to use standard wheelchairs safely and independently. Most investigators, however, intend their smart wheelchair to be a person's permanent mobility solution or have not addressed the issue at all. It is possible that using a smart wheelchair could actually diminish an individual's ability to use a standard wheelchair, as that individual comes to rely on the navigation assistance provided by the smart wheelchair. Ultimately, for some users (particularly children), smart wheelchair technology will be effective "training wheels" that can be used to teach the most basic mobility skills (e.g., cause and effect, starting and stopping on command), and for other users, smart wheelchairs will be permanent solutions.

The distinction between using a smart wheelchair as a mobility aid, a training tool, or an evaluation instrument is also worthy of study. Each of these functions is unique and requires very different behavior on the part of the smart wheelchair. As a mobility aid, the smart wheelchair's goal is to help the user reach a destination as quickly and comfortably as possible. The user is not provided feedback in order to avoid distractions and to prevent collisions. As a training tool, on the other hand, the goal is to develop specific skills. In this case, feedback is likely to be significantly increased and the extent to which the smart wheelchair complies with the user's input will be a function of the actual training activity. Finally, as an evaluation instrument, the smart wheelchair's goal is to record activity without intervention. In this case, the user would likely have no feedback or navigation assistance.

CONCLUSIONS

There are several barriers that must be overcome before smart wheelchairs can become widely used. A significant technical issue is the cost versus accuracy trade-off that must be made with existing sensors. Until an inexpensive sensor is developed that can detect obstacles and drop-offs over a wide range of operating conditions and surface materials, liability concerns will limit smart wheelchairs to indoor environments.

Another technical issue is the lack of a standard communication protocol for wheelchair input devices (e.g., joystick, pneumatic switches) and wheelchair motor controllers. There have been several efforts to develop a standard protocol (e.g., Multiple Master Multiple Slave [45]), but none has been adopted by industry. A standard protocol would greatly simplify the task of interfacing smart wheelchair technology with the underlying wheelchair.

Even if these technical barriers are overcome (and I believe they will be), issues of clinical acceptance and reimbursement still remain. Third-party payers are unlikely to reimburse clients for the expense of smart wheelchairs until they have been proven to be efficacious, if not cost- effective. Unfortunately, the evidence needed to prove efficacy will not exist until sufficient numbers of smart wheelchairs have been prescribed. This will not be possible without adequate numbers of clinicians and wheelchair technicians who have training and expertise in the use of smart wheelchair technology. Smart wheelchairs are expensive and complicated, so the familiarization and training effort will require the extensive resources and infrastructure that only the major wheelchair manufacturers (e.g., Permobil, Invacare, Pride Mobility, Sunrise Medical) possess.

This is not to imply, however, that smart wheelchair technology cannot be commercialized. Smart wheelchair technology is ready, today, for use in indoor environments that have been modified to prevent access to drop-offs. These modifications can take the form of baby gates, doors in front of stairwells, and ramps placed over single steps. The first smart wheelchair that is commercially successful in North America is likely to be marketed as a device that can be operated independently indoors, but must be controlled by an attendant outdoors or in unmodified indoor environments. However, as sensor technology improves, the environments in which smart wheelchairs can safely operate will continue to expand.

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[1] The bulleted items are quoted directly from the article.

[2] In cases where a smart wheelchair is unnamed, or named "smart wheelchair" or "intelligent wheelchair" or "robotic wheelchair," the name of the lead organization associated with the smart wheelchair is used.

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