A Semi-Autonomous Wheelchair With HelpStar

H Uchiyama, L Deligiannidis, WD Potter, BJ Wimpey, D Barnhard, R Deng, and S Radhakrishnan
Artificial Intelligence Center
University of Georgia, Athens, Georgia, USA
{potter@uga.edu, ldeligia@cs.uga.edu}

Abstract. This paper describes a semi-autonomous wheelchair enabled with "HelpStar" that provides a user who is visually impaired with mobility independence. Our "HelpStar" enabled semi-autonomous wheelchair functions more like a personal assistant, allowing much greater user independence. When the user finds themself in an unforeseen circumstance, the "HelpStar" feature can be activated to allow a remote operator to use Virtual Reality technologies to provide helpful navigational instructions or to send commands directly to the wheelchair. This paper demonstrates the successful integration of assistive technologies that allow a person who is visually impaired and using a wheelchair to navigate through everyday environments.

Keywords
Systems for Real-Life Applications, Human-Robot Interaction, Robotics, Semi-autonomous Vehicles, Virtual Reality

1. Introduction

A semi-autonomous (SA) wheelchair is an electric powered wheelchair that contains perceptual and navigational capabilities for assisting a person who is visually impaired and using a wheelchair. The goal of an SA wheelchair is to improve the independent mobility of individuals with multiple disabilities based upon integrated sensory information and human-machine interaction. In a nutshell, the SA wheelchair provides the user with enough information about the environment to allow the user to navigate effectively. This is similar to the assistance a sighted, human attendant might provide while assisting with moving the user from one location to another. The user actually controls the motions of the wheelchair but is directed by the attendant.

However, there are circumstances where the SA wheelchair user might need assistance with overcoming some unforeseen predicament. Usually, this requires the user to ask a passerby for assistance or to telephone a nearby friend to come help out. When owners of General Motors vehicles with the OnStar feature face some sort of difficulty while driving, they can request assistance from the OnStar service staff with the touch of a button. Likewise, stay-at-home customers of ADT's Companion Services contact the ADT 24-hour help staff by pressing the button on their personal alert device. Our virtual reality help system (called HelpStar) provides a similar feature but for a different type of user; the visually-impaired wheelchair user.

Figure 1: The Power Wheelchair (Invacare Nutron R-32).

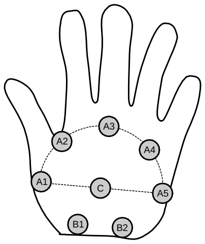

Figure 2: The arrayed motors of the Vibrotactile Glove

With the touch of a button, a member of the HelpStar staff makes contact with the SA wheelchair user having difficulty. The sensory information routinely collected by the wheelchair is instantly forwarded to the HelpStar center. This information is used to establish a virtual environment in the HelpStar center that reflects the environment encountered by the wheelchair user. This allows the HelpStar staff to analyze, diagnose, and resolve the current problem faced by the user. Corrective feedback could either be in the form of commands to the user (similar to what a local human attendant might do), or commands directly to the SA wheelchair. In either case, the user's immediate problem is resolved with the minimum amount of local interference, and they are free to continue with their activity such as going to class.

The key concept behind the HelpStar project is independence. The SA wheelchair provides an enormous amount of mobility independence to the (essentially blind, using a wheelchair) user. HelpStar provides immediate assistance when the user encounters a problem. However, more importantly, HelpStar provides security and peace-of-mind to the user; if they need help, they know help is just a button push away. The remainder of this paper describes the approach we are taking to develop the HelpStar system. We discuss the major aspects of our semi-autonomous wheelchair, the sensory information acquisition systems, and the HelpStar virtual reality feature. We conclude the paper with a discussion of the current HelpStar prototype implementation.

2. Background

Most public institutions and facilities, such as universities, provide certain types of disability services. For example, the University of Georgia provides an on-campus curb-to-curb van transportation service to students with mobility, visual, and other health-related impairments. Students with disabilities need not worry with outdoor (building to building) transportation. However, no official attendant service is provided for navigating within a university building. This is typically the case on nearly all public university campuses. In addition, many universities have a rich heritage of historic building architecture. Unfortunately, many of these older buildings are not disability friendly. Even when situated in a disability friendly building, maneuvering to a particular destination is not an easy task without the aid of a sighted human attendant.

A number of studies have been conducted in the field of assistive technology which combine robotics and artificial intelligence to develop autonomous wheelchair control. Many of these autonomous wheelchairs are equipped with a computer and a set of sensors, such as cameras, infrared sensors, ultrasonic sensors, and laser rangers. This assortment of equipment is used to address a number of specific problems such as: obstacle avoidance, local environment mapping, and route navigation. With autonomous control, the system probes the environment, detects an obstacle, plans a navigation route, makes a decision, and actually controls the wheelchair. The user simply goes along for the ride. Consequently, the system is ultimately responsible for the results, which leaves the user totally dependent upon the equipment. Most of these autonomous wheelchairs have been employed for research purposes only. *NavChair*, developed at the University of Michigan [10], transports the user by autonomously selecting three different modes (tasks): obstacle avoidance, door passage, and wall following. The *Tao* series provided by Applied AI Systems Incorporated is mainly designed for indoor use and features escape from a crowd and landmark-based navigation behaviors in addition to the three common tasks accomplished by *NavChair* [6]. *Tinman II* [13] and *Rolland* [9] also provide similar functionalities. In each case, the user is not involved with the motion of the wheelchair but is a passenger.

3. The SA Wheelchair

Many users are very comfortable with the autonomous wheelchair transportation system. However, others want to be more involved with the process. They want to feel as if they are in control; to have some feeling of independence in both the decision making and the motion involved in their day to day transportation activities. A semi-autonomous wheelchair is more like a personal assistant; the user and the wheelchair cooperate in accomplishing a task. The degree of assistance can hopefully be determined by the user in a real time manner. *Wheelesley*, one of the early research efforts in this field [17], provided semi-autonomous control of an intelligent wheelchair with a graphical interface. This allows the sighted user to control the wheelchair by selecting from among several navigational tasks. Similarly *SmartChair*, designed at the University of Pennsylvania [15], consists of a vision-based human robot interface that allows computer-mediated motion control as well as total motion control by the user. Since the man-machine interaction of these intelligent wheelchairs relies on a graphical interface, it is inappropriate for our target audience: the visually impaired person using a wheelchair.

Our goal is to customize a standard wheelchair with enough information gathering capability to allow an unsighted user to effectively control it. Our base wheelchair is a standard power chair (Figure 1) that consists of two front pivot wheels, two rear motorized wheels, a battery pack, and a controller (joystick). The perceptual navigation system consists of a computer, a collection of sensors (e.g. ultrasonic, infrared, and CCD camera), and a man-machine interface.

An SA wheelchair automatically acquires sensory inputs from the environment, processes them, and provides navigational information transformed to fit the user's available sensory resources, such as audible or tactile perception. As a man-machine interface, we developed a tactile "display" designed for the back of the hand, which consists of an array of very small vibrating motors (Figure 2: the Vibrotactile Glove). The Vibrotactile Glove conveys relatively simple navigational and environmental information by activating one or more vibrating motors, which can be intuitively interpreted by the user. By wearing the Vibrotactile Glove connected to the SA wheelchair, the user is able to expand their limited sensory perception (i.e., combine their own sensory perceptions with those of the on-board sensors) for use with navigational decision making. In other words, the user has navigational control over the wheelchair, and uses available sensory information and system commands to pilot the wheelchair.

Our SA wheelchair is designed for users with multiple disabilities (mental disabilities are excluded), specifically users with a combination of physical and sensory disabilities. In the United States over two million individuals are bound to wheelchairs, 67% of which report suffering from two or more disabilities. Likewise 1.8 million people in the United States are counted as having impaired eye-sight including blindness, 63% of which have multiple disabilities (2000 US Census data). A growing number of elderly individuals in the United States and other countries are also potential users of the SA wheelchair.

The type of assistance required to operate a wheelchair varies according to the user's operating skill and physical condition, and an SA wheelchair must provide only as much assistance as the user really needs. We have targeted a typical SA wheelchair user with severe visual impairment or blindness but who is tactilely and audibly competent with fine motor control of the upper extremities. In fact, our research efforts have been influenced by a former student with exactly the disabilities we are targeting. The result of this collaborative effort enabled us to elucidate the specific and most important problems of interest:

Collision Avoidance (including movement in reverse)
Human Detection
Drop-Off Avoidance (e.g., stair steps or sidewalk curbs)
Portal Navigation (e.g., doorways and gates)
Directional-Information Acquisition (e.g., signs and room numbers)
Building Interior Navigation (e.g., inside navigation using map/landmark information)

The first three of those tasks (Collision Avoidance, Human Detection, and Drop-Off Avoidance) are safety oriented tasks and require real time responses, while the others (Portal Navigation, Directional-Information Acquisition, and Building Interior Navigation) are navigation oriented tasks and contain a large amount of cognitive, mapping, and planning processes.

The on-board system of our SA wheelchair attempts to accomplish two of these tasks (behaviors): Collision Avoidance and Portal Navigation, in cooperation with the user. On making decisions among the behaviors, a real-time response of the system is strongly required as well as a parallel processing capability. From an architectural point of view, modularity of the system, which enables us to easily add behaviors, is also an important factor. Based upon those demands, our control architecture for the on-board system [16] utilizes an extension of the Behavior-based control system, which is widely used in the robotics field [2, 3, 4; 11, 12].

Environmental information provided by our on-board system of sensors combined with decision making information is passed to the user in the form of navigational commands. The user receives these commands through the Vibrotactile Glove where different commands are presented as different vibration sequences via the small motors.

However, there will surely be times when the user encounters a situation where they are in need of assistance. A human care attendant can assist with these sorts of emergencies, but having an attendant available all the time may not be possible and certainly does not improve independent mobility for the user. HelpStar is designed to provide the necessary assistance without the need for an attendant by utilizing virtual reality (VR) technology.

There are a number of studies that have been conducted, as well as some existing consumer applications, that employ the combination of VR with assistive technology. Most of these efforts focus upon training novice wheelchair users using a wheelchair simulator or virtual environment [1, 8]. Gundersen and his team [7] studied the use of virtual presence control on board a wheelchair at Utah State University. In their project, the on-board system was connected to the remote control booth via an RS-232 serial radio frequency (RF) link. Due to limitations with the RF band, the maximum range between the wheelchair and the remote center was approximately 1000 feet. The wheelchair was manipulated either by an attendant using the remote system or by the on-board (fully) autonomous control system. In either case, the user was not involved with control of the wheelchair.

Utilizing VR technology for remote attendance, we enrich our SA wheelchair control system by providing an "on-demand" care attendant to the SA wheelchair user. When the user hits the "HelpStar" button, the SA wheelchair control system connects to the remote attendant, the HelpStar staff member. The environmental information collected by the SA wheelchair's sensors, and the images acquired by the on-board camera(s) are transmitted to the HelpStar center via the Internet. The equipment available at the HelpStar center re-creates (in a virtual world) the situation encountered by the SA wheelchair user. Of course, the primary limitation is the necessary existence of a wireless cloud in the user's location. However, most college campuses (especially campus buildings and surrounding areas) are enclosed within a wireless cloud with direct access to the Internet.

The SA wheelchair user can select three modes of care attentiveness: observation mode, cooperation mode, and system override mode (Table 1). In observation mode, the HelpStar attendant takes on the passive role of an observer; providing no inputs to the SA wheelchair but simply observing what the wheelchair "senses" and the user's manipulations. The HelpStar attendant may provide some additional information or advice verbally through a headset to the user if they feel it is warranted. In cooperation mode, the HelpStar attendant actively controls the angles of the on-board cameras and ultrasonic sensors. Using the acquired information, the attendant may provide tactile or audible guidance to the SA wheelchair user. The user still manipulates the wheelchair movements. In the system override mode, in addition to controlling the on-board cameras and sensors, the HelpStar attendant can issue direct wheelchair movement commands. This mode can be applied when the wheelchair user is unable to drive the wheelchair, or the user is required to do another task and wheelchair operation simultaneously.

Table 1. Attentiveness of the VR system

Mode	Sensor Control	Sensor Input	Vibrotactile Glove	Motion Control
Observation	SA wheelchair	SA wheelchair HelpStar attendant	On	User
Cooperation	HelpStar attendant	HelpStar attendant	On	User
System Override	HelpStar attendant	HelpStar attendant	Off	HelpStar attendant

4. Our Current Prototype

Our current prototype development efforts are divided into two directions: the SA wheelchair, and the HelpStar system. Our SA wheelchair is described in detail in [16]. This section discusses the HelpStar prototype; our proof of concept implementation. The hardware utilized for the current HelpStar platform is a commercially available robot kit called ER1, which is supplied by Evolution Robotics [5]. The robot kit includes control software, aluminum beams and connectors for constructing the chassis, two assembled nonholonomic scooter wheels powered by two stepper motors, one 360 degree rotating caster wheel, a power module, a 12V 5.4A battery, and a web-camera. A Dell Latitude C640 laptop computer (Intel Mobile Pentium 4 processor 2.0GHz with 512 MB RAM running Windows XP) is used as the controller device. Additional accessories were also used such as a one-dimension gripper arm, infrared sensors, and additional aluminum beams and connectors. The chassis is reconfigurable and this enables us to design a chassis that would meet our needs. The laptop is equipped with a PCMCIA card that provides four additional USB ports. The ports are utilized by the web-camera, the infrared sensors, the gripper, and the stepper motors.

The software that comes with the ER1 robot, which is called the “ER1 Robot Control Center”, can be placed in three configurations.

1. Remotely control an ER1 using another instance of the Control Center on the remote machine.
2. Remotely control an ER1 using TCP/IP.
3. Control the ER1 by running behaviors.

The first configuration enables one to control the ER1 remotely from another computer using another instance of the Control Center on the remote computer. The second configuration enables one to open a TCP connection to a specified port on the Control Center and send ER1 commands to it such as move, open, close, etc. In the third configuration one can specify behaviors that the robot will execute such as find a specific object and then play a sound. More complex behaviors can be specified using Evolution’s toolkit called ERSP. With the behaviors, one can instruct the robot to find different objects or colors, and perform an action when certain conditions are met. The Control Center contains a module to recognize objects seen by the mounted web-camera. We instructed the Control Center to accept commands from a remote machine for its operations, configuration 2. We placed the camera a little bit behind the chassis in order for the gripper to be in the web-camera’s field of view. We also placed the gripper as far as possible from the laptop to avoid dropping objects accidentally on top of the laptop.

5. Interacting With The Robot

We developed a new user interface based on Virtual Reality to remotely control multiple ER1 robots (the idea being that the HelpStar center might need to provide multiple concurrent assistance). The Virtual environment consists of three dimensional objects that each represents a robot (an SA wheelchair user). These 3D objects are referred to as TVs, (televisions). The position and orientation of these TVs in the Virtual Environment are unrelated to the physical position and orientation of the robots. The TVs could be any three-dimensional objects but we utilized simple cubes. The images from the robots' web-cameras are transmitted to the remote machine utilizing RTP (Real Time Protocol). These live feeds from the robots' web-cameras are converted into images that we texture map onto the TVs; we utilized Java's Media Framework (JMF) to implement this part of the application. This enables a fully immersed person (the HelpStar attendant) to walk around the TVs and see whatever the web-cameras of the robots see.

The live feeds from the robots' cameras are transmitted to the VR machine. The VR machine is attached to an electromagnetic tracking system, LIBERTY™ [14], which consists of a six-degree-of-freedom (6DOF) tracker with three sensors; LIBERTY™ supports up to eight sensors. One sensor is attached to the Head Mounted Display (HMD) and the other two sensors are attached to the attendant's left and right hands. We also utilize two Pinch Gloves™ provided by Fakespace Systems Incorporated to recognize gestures and send commands to the robots. We have a couple of HMDs where one of them has stereo capability. We also have three different PCs that are capable of driving the application, all of which are equipped with high end video cards. The VR machine is also attached to an eye-tracking machine. We currently use the eye-tracking machine to simply select a desired TV.

The fully immersed person (the HelpStar attendant) can pick up any of the TVs, move them, rotate them, and group them together to place related TVs together. The TVs have some decoration round them to easily distinguish the different TVs. The decoration could include some other objects around the TVs or the name of the user on top of the TVs. When the attendant's hand intersects with one of the TVs and the attendant performs the gesture shown in Figure 3, the selected TV follows the motion of the attendant's hand until they release the TV as shown in Figure 4. The attendant can utilize both of his/her hands to pick up two TVs, or simply pick up one TV with one hand and hand it over to the other hand; the application is aware of two hand interaction.

Figures 3 & 4. Grasping and Releasing a TV.

The HelpStar attendant using eye-tracking technology can select one of the three dimensional objects (TVs) that represents a robot. Since the attendant may simply look around and not want to select a particular TV, to select a TV they have to look at it and then perform another gesture to select the TV being looked at. When the TV is selected, the TV's position and orientation change dynamically so that it is always in front of the attendant, even if the attendant moves around. There could be only one TV selected. To deselect a TV the attendant performs the same gesture again.

The application has nine states and is aware of state transitions; actions may be performed on a state or at a state transition. The "Idle" state is a state that indicates no communication with the robots, besides that the application is receiving live feed from the robots' cameras, and no interaction between the attendant and the TVs. While in the "Idle" state, the attendant can pick up a TV with their left or right hand, or even both. The attendant needs to touch a TV and perform a gesture to attach the TV to their virtual hand; the gesture is: touch the thumb and the index finger. As soon as the attendant releases the touching fingers, the hand-TV relationship is terminated and the TV does not follow the attendant's hand anymore. The state machine reverts back to the "Idle" state. While in the "Idle" state, the attendant can also look at a TV and then touch and release the right thumb and middle fingers to select a TV. This transitions the state machine to the "Selected" state where the TV is locked in front of the attendant's field of view. As the attendant moves around, the TV appears in front and the attendant does not see the rest of the Virtual Environment that primarily consists of other TVs. This is the main state of the state machine where the attendant can either deselect the TV or send commands to the robot. To set the speed to slow or fast the attendant "pinches" the left thumb and index fingers and the left thumb and middle fingers respectively. The speed reflects the linear speed not the rotational/angular speed. Slow speed is the slowest the robot can move which is 5 cm/sec and the fast speed is the fastest the robot can move, which is 50 cm/sec. Note here that the speed is set at the transition from the "Speed_fast" or "Speed_slow" states to the "Selected" state. The gripper operates using the left thumb and the left pinky and ring fingers. As long as the state machine is in one of the "Gripper_open" or "Gripper_close" states, the gripper keeps opening or closing respectively. Upon releasing the fingers the state machine transitions to the "Selected" state at which point the "stop" command is transmitted. The stop command instructs the robot to cancel any operation that is being executed. This enables the attendant to partially open or close the gripper.

The other two states are used to maneuver, rotate left or right, and move forward or backwards, the robot. When the state machine transitions from either the "Move" or "Rotate" states to the "Selected" state the "stop" command is transmitted to stop the robot. We use two states, one for the rotation and one for the move because of the robot's limitations. An ER1 cannot move and at the same time rotate. So, either the attendant can instruct the robot to move straight (forward or backwards) or rotate (clockwise or counterclockwise). To instruct the robot to move forward, the attendant needs to simply lean forward and pinch the right thumb and pinky fingers. Similarly, to instruct the robot to move backwards the attendant simply needs to lean backwards and perform the same pinch. Since there is a Polhemus 3D sensor attached to the attendant's HMD to track their position and orientation in space, we define a plane in space that divides the space into two parts. We keep track of the attendant's position orientation continuously and upon the appropriate gesture we define the plane in space.

The attendant can move between the divided space to instruct the robot to move forward or backwards.

To instruct the robot to rotate clockwise or counterclockwise, the attendant first needs to perform the right gesture for the state machine to transition to the "Rotate" state at which point the robot follows the rotation of the attendant's head. If the attendant rotates his/her head 20 degrees to the left, the robot also rotates 20 degrees to the left. Since the robot's motors are not as fast as the attendant's head rotation speed, the attendant should rotate slowly to give enough time to the robot to perform the rotation. The rotation angle we are tracking in real time is the rotation around the Y axis, which is pointing upwards.

The rotation or direction of the robot depends on local coordinates. That means that even if the attendant rotates his/her body 180 degrees, forward means forward to the robot and the attendant's left means left to the robot, something that is not true if one tries to maneuver the robot using a conventional mouse. Even if one uses the "Control Center" to remotely control the ER1, changing the speed of the robot would require multiple mouse clicks on different windows. However, utilizing a Virtual Reality interface makes operating an ER1 remotely seem more natural and the attendant can send more commands to the robot by simple gestures/postures.

6. Conclusions & Future Directions

HelpStar is our proposed system for remote assistance to a semi-autonomous wheelchair user using Virtual Reality as an invisible assistive service. The system is specifically designed for individuals who are visually-impaired, use a wheelchair, and want to be involved with their own mobility. A single HelpStar attendant can virtually see multiple users and provide immediate assistance to one or more of them. The SA wheelchair employed in the design allows the user to expand their limited sensory perception for use in navigational decision making. If the SA wheelchair user encounters an unusual situation, all they have to do is push a button to contact the HelpStar center. The key idea, the feature that makes this all worthwhile, is to provide mobility independence to the user.

To demonstrate the feasibility of this concept, the HelpStar prototype currently uses a commercially available robotics kit from Evolutionary Robotics called the ER1. The Virtual Reality environment enables a fully immersed person, the HelpStar attendant, to sense what the robots sense from a remote location. Upon selecting one robot using the PinchGloves, the attendant can control and move the ER1 using simple motion commands in a natural manner, perhaps to gain a better visual foothold of any situation. Once the SA wheelchairs are introduced into the equation, we will be able to begin actual field trials. We expect these to begin during the summer of 2005.

References

1. Adelola, I. A., Cox, S. L., and Rahman, A., (2002). Adaptive Virtual Interface for Powered Wheelchair Training for Disabled Children, In *Proc. of 4th Intl. Conference of Disability, Virtual Reality & Assoc. Technology*, Veszprém, Hungary, pp. 173-180.
2. Arkin, R. C., (1998). *Behavior-based robotics.* The MIT Press: Cambridge, Mass.
3. Brooks, R. A., (1991a). "How to Build Complete Creatures Rather than Isolated Cognitive Simulators." In K. VanLehn (ed.), *Architectures for Intelligence*, pp. 225-239, Lawrence Erlbaum Associates, Hillsdale, NJ.

4. Brooks, R. A., (1991b). “Integrated Systems Based on Behaviors.” *SIGART Bulletin* 2, 2(4), pp. 46-50.
5. Evolution Robotics, (2004), Evolution Robotics ER1 Robot Kit, Retrieved October 12, 2004, from http://www.evolution.com/education/er1/
6. Gomi, T. and Griffith, A. (1998) Developing intelligent wheelchairs for the handicapped. In Mittal et al. eds., *Assistive technology and AI*. LNAI-1458, Berlin: Springer-Verlag, pp. 150-78.
7. Gundersen, R. T., Smith, S. J., and Abbott, B. A. (1996) Applications of Virtual Reality Technology to Wheelchair Remote Steering System, In *Proc. of 1st Euro Conf of Disability, Virtual Reality & Assoc. Technology*, Maidenhead, UK, pp. 47-56.
8. Inman, D. P., and Loge, K. (1995). Teaching Motorized Wheelchair Operation in Virtual Reality. In *Proceedings of the 1995 CSUN Virtual Reality Conference*. Northridge: California State University, Retrieved October 1, 2004 from http://www.csun.edu/cod/conf/1995/proceedings/1001.htm
9. Lankenau, A., Röfer, T. and Krieg-Bruckner, B. (2003) Self-localization in large-scale environments for the Bremen Autonomous Wheelchair. In Freksa and et al. eds., *Spatial Cognition III*. LNAI-2685. Berlin: Springer-Verlag, pp. 34-61.
10. Levine, S.P. and et al. (1999) The NavChair Assistive Wheelchair Navigation System. *IEEE Transactions on Rehabilitation Engineering* 7(4): pp. 443-51.
11. Matarić, M. J., (1991). “Behavioral Synergy without Explicit Integration.” *SIGART Bulletin* 2, 2(4), pp. 130-133.
12. Matarić, M. J., (1992). “Behavior-Based Control: Main Properties and Implications.” *Proc. of IEEE Int.l Conf. on Robotics and Automation, Workshop on Architectures for Intelligent Control Systems*, Nice, France, May, pp. 46-54.
13. Miller, D. (1998) Assistive robotics: an overview. In Mittal et al. eds., *Assistive technology and AI*. LNAI-1458. Berlin: Springer-Verlag, pp. 126-136.
14. Polhemus Inc., (2004), LIBERTY™ , Retrieved October 12, 2004, from http://www.polhemus.com/LIBERTY™ .htm
15. Rao, R. S. and et al. (2002) Human Robot Interaction: Application to Smart Wheelchairs. *Proc. of IEEE International Conference on Robotics & Automation*, Washington, DC, May 2002, pp. 3583-3588.
16. Uchiyama, H. (2003) Behavior-Based Perceptual Navigational Systems for Powered Wheelchair Operations, *Master Thesis Proposal at the University of Georgia*, Retrieved October 11, 2004, from http://www.cs.uga.edu/~potter/robotics/HajimeThesisProposal.pdf
17. Yanco, H. A. (1998) Integrating robotic research: a survey of robotic wheelchair development. *AAAI Spring Symposium on Integrating Robotic Research*, Stanford, California.