October 2003

Human Robot Interaction and Usability Studies for a Smart Wheelchair

Sarangi P. Parikh
University of Pennsylvania

Rahul Rao
University of Pennsylvania

Sang-Hack Jung
University of Pennsylvania

R. Vijay Kumar
University of Pennsylvania, kumar@grasp.upenn.edu

James P. Ostrowski
University of Pennsylvania

See next page for additional authors

Abstract
We build on previous work [12], [14] on the development of a computer controlled wheelchair equipped with a suite of sensors and a novel interface for human-robot interaction. In this paper, we present experimental results and usability studies for the wheelchair. The architecture for human-robot interaction is hierarchical, with the lowest level corresponding to trajectory control, the intermediate level being behavioral and the highest level involving the composition of behaviors and navigation. Our experimental results illustrate the benefits of a shared-control paradigm where the human operator selects the appropriate hehavior(s) or goals while the software is responsible for executing behaviors and generating safe trajectories. Experiments with human users highlight advantages of augmentation in wheelchairs.

Author(s)
Sarangi P. Parikh, Rahul Rao, Sang-Hack Jung, R. Vijay Kumar, James P. Ostrowski, and Camillo J. Taylor

Proceedings of the 2003 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Las Vegas, Nevada · October 2003

Human Robot Interaction and Usability Studies for a Smart Wheelchair

Sarangi P. Parikh*, Rahul Rao*, Sang-Hack Jung†
Vijay Kumar*, James P. Ostrowski*, Camillo J. Taylor†
*Mechanical Engineering and Applied Mechanics, †Computer and Information Science
GRASP Laboratory, University of Pennsylvania
{sarangi,rahulrao,sangj,kumar,jpo,cjtaylor}@grasp.cis.upenn.edu

***Abstract*— We build on previous work [12], [14] on the development of a computer controlled wheelchair equipped with a suite of sensors and a novel interface for human-robot interaction. In this paper, we present experimental results and usability studies for the wheelchair. The architecture for human-robot interaction is hierarchical, with the lowest level corresponding to trajectory control, the intermediate level being behavioral and the highest level involving the composition of behaviors and navigation. Our experimental results illustrate the benefits of a shared-control paradigm where the human operator selects the appropriate behavior(s) or goals while the software is responsible for executing behaviors and generating safe trajectories. Experiments with human users highlight advantages of augmentation in wheelchairs.**

I. INTRODUCTION

There are numerous examples of partially autonomous systems in which the low level controllers are autonomous while the human user is primarily responsible for decision making at the higher levels. An important class of these systems are mobile agents with embedded computers that are directly controlled by a human pilot or navigator in the control loop. The user's ability to interact with the embedded computer, actuators, and sensors is important in influencing the performance of such human-in-the-loop systems [15].

Our focus in this article is on smart wheelchairs (Figure 1), devices that can potentially benefit over 5 million individuals in the U.S. alone. Current systems have very little computer control, except at the lowest levels of control. Interfaces are similar to those found in passenger cars. The rider has to continuously specify the direction, and in some cases, the velocity of the chair using a joystick like device. In cases where the level of neuro-muscular control is poor, joysticks are used to specify directions while the choice of speed is limited to a safe constant value.

There is extensive research on computer-controlled chairs where sensors and intelligent control algorithms have been used to minimize the level of human intervention [10], [11], [16], [18]. Many efforts have used sensors and low-level controllers to guarantee safety by monitoring human commands which may cause chairs to approach risky states. By taking a survey of assistive devices, it can be noted that most of the challenges in building an autonomous chair stem from the lack of robustness of motion planning, perception, and control algorithms [9]. In our work, we show that by allowing the human user to make higher level decisions, we are able to use sensory information and simple control algorithms to robustly control the wheelchair, allowing the user to navigate unstructured environments.

Our research goal is to design and develop a system that allows the user to easily interact with the robot at different levels of the control and sensing hierarchy. At the lowest level, the user can drive the chair through a conventional joystick-like interface. At a higher level, the user can select from a range of behaviors such as hallway navigation, or moving forward while avoiding obstacles. At an even higher level, the user is able to specify a destination while the system automatically selects behaviors and plans paths to guide the chair to the goal. In intelligent buildings, where maps are made available through a wireless network, the user would be able to specify destinations on the map allowing the chair to automatically navigate to that location.

Our prototype wheelchair called the SMARTCHAIR is described in [12], [14]. The next section provides a brief summary of our previous work, including a description of the experimental platform. The motion control algorithms used for navigation are described in Section 3. The main goal of the paper is to present experimental results from usability studies conducted on the wheelchair. This is the subject of Section 4. We conclude with a brief summary including directions for future work in Section 5.

II. The SMARTCHAIR

Our motorized wheelchair is equipped with onboard processing and a suite of sensors as seen in Figure 1. An omni-directional camera, mounted over the user's head, allows the user to view 360 degrees around the wheelchair. A projector displays images and other information acquired by the wheelchair sensor onto the laptray and enables the user to send commands to the wheelchair through a visual interface. The user can select actions by pointing on a simple, visual interface that is projected on the laptray. This interface is utilized to select targets in the omnidirectional images, including hallways and doorways

0-7803-7860-1/03/$17.00 © 2003 IEEE

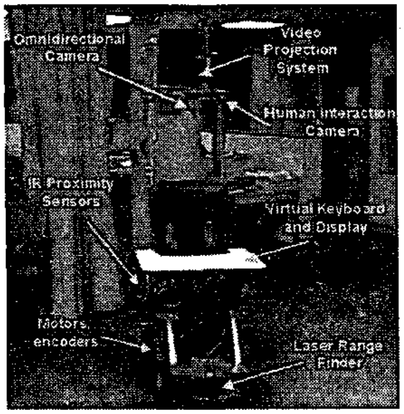

Fig. 1. The GRASP Laboratory SMARTCHAIR

to be traversed. User input is accomplished by monitoring the image projected onto the laptray and the user's actions through an overhead video camera. Figure 2 shows a view of this interface as seen from the user's perspective. The projector and camera systems act in concert forming a feedback system where the user interaction is effected by occluding various parts of the projected image.

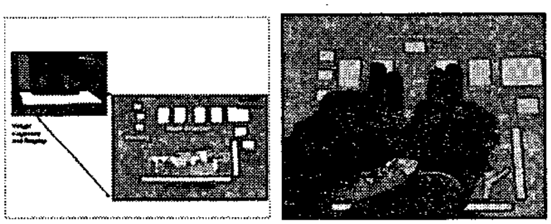

Fig. 2. The robot eye view of the world and the control modes available for selection (left). The user can select modes and issue commands by occluding appropriate regions in the display (right).

The scheme hinges on the observation that the relationship between the three surfaces of interest—the work surface, the visual interface and the image obtained by the camera—can be characterized by projective transformations of $\mathbb{RP}^2$. Further details of the the interaction system as well as the transformations can be found in [14].

The basic advantage of this vision based interaction technique is that it does not involve mechanical input devices such as keyboards, mice and touch screens. There are no moving parts and no wires to connect to the interface surface. Thus, the system designer is allowed to specify the layout and action of the user interface entirely in software without being constrained by a fixed mechanical interface. This flexibility can be used to customize interfaces to the requirements and capabilities of individual users. Further, the interface can be switched off when not in use, freeing the laptray for other uses.

III. COMPUTER-MEDIATED MOTION CONTROL

We have developed a hierarchical architecture for our robotic system. At the lowest level of interaction, the user can issue direct commands to the motors and guide the wheelchair around, much like he or she would with a joystick. The intermediate level of interaction would typically correspond to the user making certain decisions but not issuing direct commands to steer the chair as in the previous case. The lower level tasks are now handled by the system itself once the higher level decisions are made. At the highest level, the user can issue a navigation command that would guide the chair to a desired destination. It is envisioned that at a later stage of development, such a high level decision would correspond to the user selecting a destination on a map of the surroundings presented via the interface. Once this is done the system would be capable of interpreting that choice and taking the user there, automatically planning paths, choosing modes and composing the appropriate behavior.

The developed interface, which enables the user to interact with the control hierarchy described above is flexible. Figure 2 shows a user interacting with the interface in one of the modes of operation. The entire design of the interface in software renders it especially suitable for customization. This can be done without hardware changes to the wheelchair.

Some typical actions of a wheelchair user include approaching and passing through designated doors; going to specified locations in the environment, such as windows or closets; going to the front of a desk or a computer; or steering down hallways. Thus, we use simple and reliable modes or behaviors as building blocks to execute these tasks. Combinations of different modes via seamless and smooth switching, enable the user to accomplish her daily tasks as efficiently as possible. Additional details of how these tasks are executed as well as some preliminary tests conducted to evaluate them are discussed in the next section.

IV. EXPERIMENTS AND ASSESSMENTS

In this section we show how simple controllers can be used for navigation and present experimental results that illustrate the performance of the system as well as the main benefits of augmentation. We consider three representative modes— driving to a desired location, navigating along a hallway, and traversal through doorways. Further, we also present results obtained by the composition of each of these modes with an obstacle avoidance mode.

A. Description of Experiments

First, we consider the simplest task in which the user designates a target in the image and the chair navigates to the target. The target may be visible to the human (*i.e.*, within her line of sight) or hidden from view, but visible on the display. Our goal via the first set of experiments is to enable the user to reach a target that may or may not be visible. When the user points to the target, the chair travels to the position indicated on the image. In the presence of obstacles, the chair performs a simple obstacle avoidance maneuver, but returns to the task of reaching the target.

Second, we consider tasks in which the user designates a feature like a wall or a lane for navigation. A simple representative task is hallway navigation. The chair navigates the hallway, along the center of the hallway while avoiding obstacles, until it comes either to an obstacle it cannot circumvent or to the end of the hallway.

Third, we consider tasks in which the user identifies a feature like a desk or a door, and the chair goes to the feature while maintaining an appropriate orientation. We choose the representative task of navigating through a doorway, where the user specifies the doorway, and the chair goes through the doorway.

We chose to report on these tasks because they are representative of tasks that a wheelchair user performs routinely and also because they are particularly useful in illustrating the benefits of robotic augmentation. Each of these tasks is accomplished by behaviors. The detailed description of the controllers used in each behavior is presented in [13].

All three experiments are performed with and without obstacles, with four users, and in two different modes. In the manual mode, the user uses a joystick to drive the chair, while in the autonomous mode, the user specifies behaviors using the human augmentation software.

The objective of the experiments is to evaluate the performance of the augmentation software and of the human user under different conditions. The criteria we use for this evaluation are:

1) The total time it takes to complete a given task—this may be influenced by other factors such as the placement of obstacles, which may affect the speed at which a user drives the chair.
2) The number of times a user interacts with the interface—these interactions are occur when the user makes such decisions as mode selection or switching. We simply use the number of times the user points to the screen as a measure of the complexity of the human robot interaction. We acknowledge that this is not a measure of the underlying cognitive process, which is quite complex. However, in the absence of other measures, we use this as an indicator of human robot interaction.
3) The number of times the chair is unable to avoid obstacles—this also includes situations where dynamic obstacles appear in the wheelchair's path in both manual and autonomous cases.

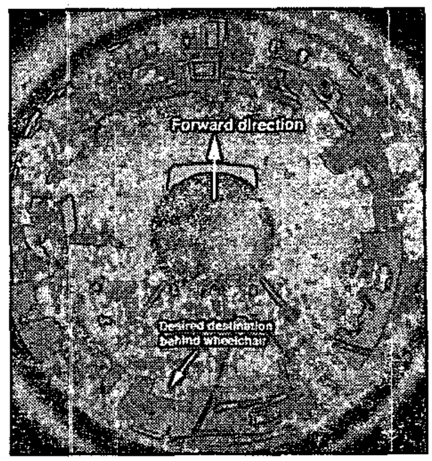

Fig. 3. A view of the surroundings displayed on the laptray as seen by the user.

We represent ground truth by using odometry from the wheelchair. Simple tests conducted to observe factors that could contribute to irregularities in odometry, such as belt or wheel slippages, reveal that such slip is minimal or not existent in our test environment. Quantitatively, over a distance of 8 meters, these tests show an average deviation of 0.03 meters in the longitudinal direction and about 0.18 meters in the transverse direction for various travel velocities ranging from 0.25 m/sec to 0.6 m/sec. Thus, in the transverse direction the average error is 2.5%. Since our tests show only slight deviations from an ideal performance, we accept odometry as ground truth in this paper.

B. Results

1) Navigation to Targets: This set of experiments includes cases when the user cannot see the destination in her visual field-of-view. The example shown has the target located behind the wheelchair. The target, in this case, cannot be seen by the person, but can be seen in the image (Figure 3). The user simply selects the target and the autonomous mode drives the chair to the target. Figure 4 demonstrates that we are able to detect and navigate to the selected location from various initial poses. The arrows indicate the initial positions and orientations of the wheelchair. Although the chair reaches its desired destination, it is important to reiterate that there may be a marginal overshoot due to inaccuracies in the omnicam image, which is not seen in the figure.

Figure 5 shows the paths taken by the wheelchair towards a desired destination from different starting poses in the presence of obstacles in the environment. This motion is a composition of two control modes— navigation to a target and obstacle avoidance. To clarify, it is important to

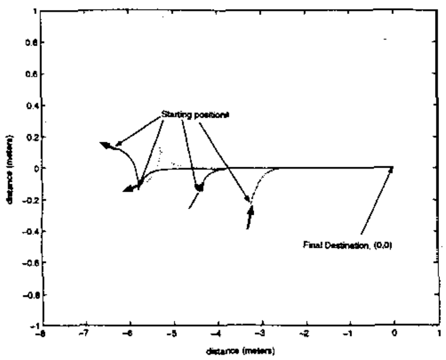

Fig. 4. Trajectories from autonomous navigation to a target from various initial poses in the absence of obstacles.

note that in the autonomous mode, the user simply locates the desired destination in the image and clicks. This activates the augmentation software to work in tandem with the sensors on the system to guide the chair to its destination.

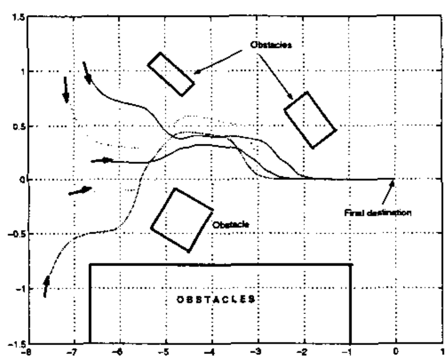

Fig. 5. Autonomous navigation to a target from various initial poses in the presence of obstacles.

2) Hallway Navigation: In this set of experiments, we look at hallway navigation in obstacle free environments. In Figure 6, we plot the trajectories various users take when asked to navigate straight down the hallway. Figure 7 shows the trajectories the wheelchair follows while autonomously driving down the hallway. In the automated case, the chair follows the same trajectory each time and is able to efficiently and predictably navigate the hallway. Although the human users can achieve the task, they are unable to guide the wheelchair as smoothly down the hallway as in the autonomous mode. The number of interactions are also noted. In the manual mode, the user needs to continuously monitor the actions of the chair and act appropriately. In this simple manual hallway navigation experiment, the average number of interactions

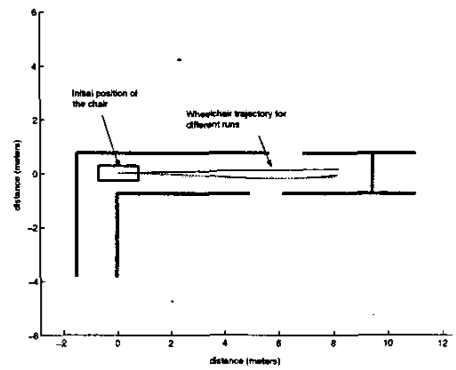

Fig. 6. Manual hallway navigation: these are trajectories taken by human users without any assistance from the autonomous control system.

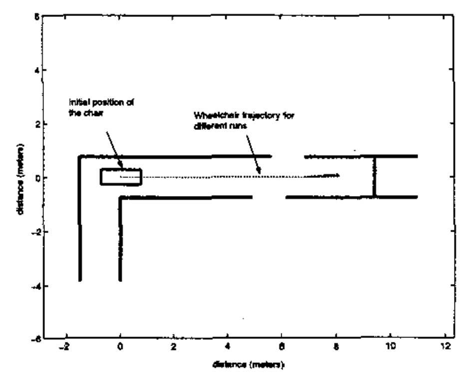

Fig. 7. Autonomous hallway navigation: trajectories taken by the automated system without any human assistance.

by the user was 6 as compared to 1 in the autonomous case.

3) Doorway Navigation: In this case, the user is asked to navigate towards the doorway starting from several different positions and orientations (Figure 8). During the manual mode, the user must continuously steer towards the doorway, requiring several interactions with the system. By contrast, the user chooses the feature in the autonomous mode and the system then guides its way to the door using sensory feedback. No further user interactions are required. The times for completion for the two cases are comparable in this scenerio, while the number of human robot interactions clearly show the advantage of the automated system (Table I).

4) Unmodeled Obstacles: We have implemented a simple obstacle avoidance algorithm on our platform. If obstacles are detected within the specified minimum distance around the wheelchair, the obstacle avoidance algorithm is activated. The detection of objects is done by the laser scanner. When the obstacle avoidance algorithm is

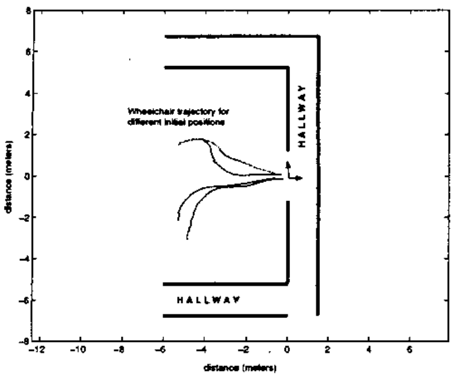

Fig. 8. Autonomous Doorway Navigation: trajectories taken by the automated system without any human assistance.

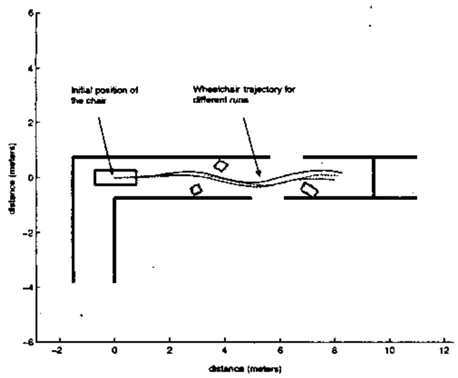

Fig. 9. Manual hallway navigation with obstacles. This shows the various trajectories that the different users take to navigate the hallway with obstacles present.

activated, the chair smoothly avoids the obstacle by going around it while also continuing towards its destination.

In further experiments, we added obstacles to the two environments studied to see how the augmented system compares to the manual mode. First, the users were asked to navigate through the hallway avoiding the obstacles. In Figure 9, the paths that four users took are plotted. We compare this to the autonomous vehicle, which is shown in Figure 10.

As seen in the figures, neither the chair, nor any of the users collide with any of the obstacles. However, the automated wheelchair has a more predictable trajectory. The average time to completion for the chair (28 seconds) is much faster than the human user's average time of 50 seconds. The average number of interactions the user has with the chair is 25, while the autonomous mode only requires one interaction at the beginning when mode selection takes place.

More experiments are done with obstacles in the door

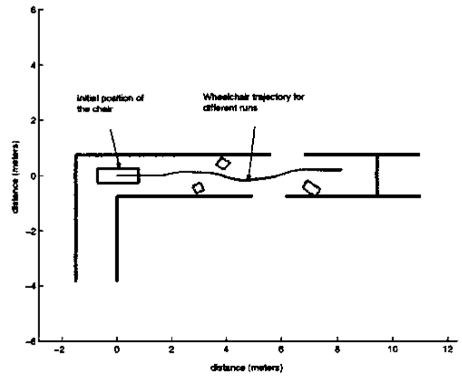

Fig. 10. Autonomous hallway navigation with obstacles. This illustrates the predictable trajectory of the automated wheelchair system.

traversal environment. An obstacle is placed in front of the doorway so that the system must navigate around it. In this case, depending on the initial position and orientation, the obstacle may or may not obstruct the path towards the doorway. Again, manually, there are variations in trajectories taken by the users. However, the human user is comparable to the autonomous vehicle in this environment.

C. Metrics

From these experiments we conclude that the autonomous system functions just as well as or better than the human user when there are obstacles. In the hallway, it works much better and is smoother. In the door traversal trials, the chair and the human are similar. The results from these experiments are summarized in Table I.

Experiment	Time (manual)	# HRI (manual)	Time (auto)	# HRI (auto)
Nav. to hidden target	45 sec.	14	28 sec.	1
Hall Nav.	44 sec.	6	25 sec.	1
Hall Nav. w/ obst.	50 sec.	25	28 sec.	1
Door Nav.	35 sec.	12	30 sec.	1
Door Nav. w/obst.	40 sec.	13	35 sec.	1

TABLE I

MANUAL VERSUS AUTONOMOUS NAVIGATION

In the next set of experiments, we look at what happens when an obstacle suddenly appears in front of the wheelchair. While the user is navigating the hallway, an obstacle is suddenly placed in front of the user to see how quickly the user is able to react. In two of the four cases, the person collided into the obstacle before stopping

User	T_c (s)	D_c (m)	T_s (s)	D_s (m)
Man 1	2.0	0.44	1.97	0.01
Man 2	2.0	0.44	1.69	0.07
Man 3	2.0	0.44	2.72	collision
Man 4	2.0	0.44	3.46	collision
Auto Avg.	2.0	0.44	1.50±0.15	0.20±0.04

TABLE II

RESULTS FOR DYNAMIC OBSTACLE AVOIDANCE

the chair. The same tests done on the automated system are shown in Table II, where T_c and D_c, are the time to collision and the distance to collision at the instant that the obstacle is introduced. T_s is the time it takes to stop, while D_s is the distance at which the chair stops in front of the obstacle. Our studies demonstrate that the autonomous vehicle is able to react faster and therefore, avoids hitting the obstacle each time.

V. CONCLUSIONS

In this paper, we presented experimental results with our SMARTCHAIR, which features a novel vision-based human interface, computer-mediated motion control algorithms, and a hierarchical human-robot interaction paradigm. The most significant advantage of the system is the ease with which the human operator can select such behaviors as go to designated target points in the environment or follow and track features while avoiding obstacles. Another important aspect is the ability of the user to be aware of features in the environment that are not directly in the line of sight. Our experiments with several subjects (Table I) show that simple tasks such as navigating to specified targets or features can be accomplished faster with a single touch. In contrast, manual navigation requires continuous monitoring or control via a joystick-like interface. The experiments also illustrate faster response time to dynamic changes in the environment, suggesting that such systems can be potentially safer and easier to deploy. Our future work is directed toward composing simple robot behaviors and designing an interface that might allow the user to compose behaviors in a sensible manner while preventing unsafe actions.

Acknowledgments

We gratefully acknowledge support from NSF grant IIS-0083240 and DUE-9979635.

VI. REFERENCES

[1] Avizzano, C.A., and Bergamasco, M. Technological Aids for the Treatment of Tremor. *International Conference on Rehabilitation Robotics, Stanford, CA (1999).*

[2] Dufour, B. Augmentation for Human- Worn Devices, *Master's Thesis, University of Pennsylvania, 1998.*

[3] Dutta-Roy, A. Networks for homes. *IEEE Spectrum, Vol. 36, No. 12.*

[4] Eberst, C., Anderson, M., Christensen, H.I., Vision Based Door traversal for Autonomous Mobile Robots *Proceedings of the 2000 IEEE/ RSJ International Conference on Intelligent Robots and Systems*

[5] Faugeras, Olivier, *Three- Dimensional Computer Vision, MIT Press 1993.*

[6] Horswill, I., Polly: A Vision-Based Artificial Agent. *In Proceedings of the Eleventh National Conference on Artificial Intelligence (AAAI-93), July 11-15, 1993, Washington DC, MIT Press*

[7] Access and Productivity Tools, IntelliTools Inc., www.synapseadaptive.com, 1999.

[8] Krovi, V., Anathasuresh, G. K. and Kumar, V. Design and Virtual Prototyping of Customized Rehabilitation Aids. *ASME Journal of Mechanical Design, 1999.*

[9] Kumar, V., Rahman, T., and Krovi V. Assistive Devices for People with Motor Disabilities. *Wiley Encyc. for Electrical and Electronic Engineers, Ed. J. Webster, 1997.*

[10] Levine, S., Koren, Y., and Borenstein, J. NavChair Control System for Automatic Assistive Wheelchair Navigation. In the *Proceedings of the 13th Annual RESNA International Conference, Washington, D.C.: RESNA, 193-194 (1990).*

[11] Orpwood, R. D., Design Methodology for Aids for the Disabled. *Journal of Medical Engineering and Technology, Vol. 14, No. 1, 1990, pp. 2- 10.*

[12] Patel, S., Jung, S. H., Ostrowski, J., Rao, R. S., Taylor, C. J., Sensor Based Doorway Navigation for a Nonholonomic Vehicle, *International Conference on Robotics and Automation, Washington, D.C., 2002.*

[13] Parikh, S. P., Rao, R. S., Jung, S. H., Kumar, V., Taylor, C. J., Ostrowski, J. P., SmartChair: A Simple Framework for Computer Mediated Motion Control, *submitted to Journal of Neural Systems and Rehabilitation Robotics, 2003.*

[14] Rao, R. S., Conn, K., Jung, S. H., Katupitiya, J., Kientz, T., Kumar V, Ostrowski, J, Patel, S., Taylor, C. J., Human robot interaction: Applications to smart wheelchairs,*International Conference on Robotics and Automation, Washington, D.C., 2002.*

[15] Rahman, T., Harwin, W., Chen, S., and Mahoney, R., (1994). Rehabilitation Robot Control with Enhanced Sensory Feedback. *4th International Conference on Rehabilitation and Robotics, Wilmington, DE, June 14-16, pp. 43-48.*

[16] Simpson, R., Poirot, D., Baxter, M.F. Evaluation of the Hephaestus Smart Wheelchair System. *International Conference on Rehabilitation Robotics, Stanford, CA (1999).*

[17] Camillo J. Taylor, Virtual Keyboards, *Technical Report, GRASP Laboratory, 1999.*

[18] Wagner, J.J., Van der Loos, H.F.M., Smaby, N., Chang, K., and C. Burgar, C., ProVAR Assistive Robot Interface. *International Conference on Rehabilitation Robotics, Stanford, CA (1999).*