the wheelchair's battery-charging socket and draws power equally from both batteries.

5) Embedded Processing: During development of the prototype, it was useful for debugging purposes for the control software to run on a notebook computer on board the wheelchair. However, a laptop computer is impractical for the finished product for several reasons. First, the laptop's display can distract the user's attention and block the user's field of view. Second, a laptop is much too expensive. Finally, the operating systems on most laptop computers do not support real-time operations.

The control software developed for the prototype was written using Microsoft Visual C++ and the Windows95 operating system. This was chosen to facilitate porting the code to the WindowsCE operating system, which runs on a variety of inexpensive microprocessors. Once the control software has been refined, we expect to transfer the software to a dedicated microprocessor running a real-time operating system. An embedded microprocessor can provide equivalent performance and power consumption at a price decreased by several orders of magnitude, and a real-time operating system will provide more robust operation than Windows95.

IV. Discussion

The prototype described in this paper represents the first step toward the development of a commercially available smart wheelchair system that is compatible with multiple brands of power wheelchairs. To date, we have demonstrated that it is possible to provide effective obstacle avoidance without requiring modifications to the underlying power wheelchair. We have also developed an approach to integrating our system with power wheelchairs that works in the absence of an accepted "wheelchair bus" standard for attaching external components to a wheelchair.

Future work on the prototype will proceed on several fronts. The design issues discussed in Section III-C must be addressed as the project continues to move toward a marketable prototype. In addition, the Hephaestus Smart Wheelchair System will be used as the testbed for research into automatic adaptation and mobility training.

Acknowledgment

The Lancer2000 wheelchair was donated to Texas Robotics and Automation Center (TRACLabs) by Everest and Jennings.

References

[1] J. Borenstein and Y. Koren, "Histogramic in-motion mapping for mobile robot obstacle avoidance," *IEEE Trans. Robot. Automat.*, vol. 7, pp. 535–539, Aug. 1991.

[2] ——, "The vector field histogram—Fast obstacle avoidance for mobile robots," *IEEE Trans. Robot. Automat.*, vol. 7, pp. 278–288, Apr. 1991.

[3] R. P. Brinker and M. Lewis, "Making the world work with microcomputers," *Exceptional Children*, October 1982.

[4] J. J. Campos and B. I. Berenthal, "Locomotion and psychological development in infancy," in *Childhood Powered Mobility: Developmental, Technical and Clinical Perspectives*, Seattle, WA, Mar. 6, 1987, RESNA Conf. Proc., pp. 11–42.

[5] M3S Consortium, "M3S protocol specification," M3S Consortium, Delft, Netherlands, vol. 16, Apr. 1993.

[6] R. Dixon, D. Carnine, and E Kameenui, "Curriculum guidelines for diverse learners," in *Monograph for National Center to Improve the Tools of Educators*. Eugene, OR: Univ. of Oregon, 1996.

[7] J. Douglass and M. Ryan, "A pre-school severely disabled boy and his powered wheelchair: A case study," *Child Care, Health Develop.*, vol. 13, pp. 303–309, 1987.

[8] G. Dudek and M. Jenkin, *Computational Principles of Mobile Robotics*. Cambridge, U.K.: Cambridge Univ. Press, 2000.

[9] L. Fehr, W. Langbein, and S. Skaar, "Adequacy of power wheelchair control interfaces for persons with severe disabilities: A clinical survey," *J. Rehab. Res. and Develop.*, vol. 37, no. 3, May/June 2000.

[10] D. Kelly, "The enhancement of mobility for individuals who are both physically and visually disabled," in *Proc. RESNA'99 Annu. Conf.*, Long Beach, CA, RESNA, pp. 227–229.

[11] S. Levine, D. Bell, L. Jaros, R. Simpson, Y. Koren, and J. Borenstein, "The NavChair assistive wheelchair navigation system," *IEEE Trans. Rehab. Eng.*, vol. 7, pp. 443–451, Dec. 1999.

[12] R. Murphy, *An Introduction to AI Robotics (Intelligent Robotics and Autonomous Agents)*. Cambridge, MA: MIT Press, 2000.

[13] K. Paulsson and M. Christoffersen, "To develop 'On Track': Severely multi-handicapped children with developmental delay can drive electric wheelchairs with loop-tape steering," Karolinska Inst., Stockholm, Sweden, 1991.

[14] L. Rosenbloom, "Consequences of impaired movement: A hypothesis and review," in *Movement and Child Development*, K. S. Holt, Ed. London, U.K.: SIMP, 1975.

[15] I. Ulrich and I. Nourbakhsh, "Appearance-based obstacle detection with monocular color vision," in *Proc. AAAI 2000*. Austin, TX, Aug. 2000, pp. 866–871.

[16] G. Verburg, L. Balfour, E Snell, and S. Naumann, ""Mobility training in the home and school environment for persons with developmental delay," Final Report to Ontario Mental Health Foundation and Ministry of Community and Social Services' Research and Program Evaluation Unit, 1991.

[17] B. A. Wright, *Physical Disability—A Psychosocial Approach*. New York: Harper & Row, 1983.

Voice Control of a Powered Wheelchair

Richard C. Simpson and Simon P. Levine

***Abstract*—Several researchers have described voice control mechanisms for a power wheelchair, but voice control has yet to become a commercially viable control alternative. One problem with voice control is that the voice's limited bandwidth renders it impossible to make frequent small adjustments to the wheelchair's velocity. One possible solution is to utilize voice control in combination with the navigation assistance provided by "smart wheelchairs," which use sensors to identify and avoid obstacles in the wheelchair's path. This paper describes an experiment that compares the performance of able-bodied subjects using voice control to operate a power wheelchair both with and without navigation assistance.**

I. Introduction

The variation in functional abilities presented by power wheelchair users is clearly illustrated by the vast array of wheelchair controllers that are available. Voice control has long been pursued as a control mechanism for wheelchairs [1], [2], [5], [6], but even though it has proven useful for operating other assistive technologies such as computers and environmental control systems, voice control has yet to become a viable wheelchair control method.

Manuscript received February 8, 2002.

R. C. Simpson was with Texas Robotics and Automation Center (TRACLabs), Houston, TX 77058 USA. He is now with the Department of Rehabilitation Science and Technology, University of Pittsburgh, Pittsburgh, PA 15260 USA.

S. P. Levine is with the Rehabilitation Engineering Program, Department of Physical Medicine and Rehabilitation, Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI 48109 USA.

Publisher Item Identifier S 1534-4320(02)05942-9.

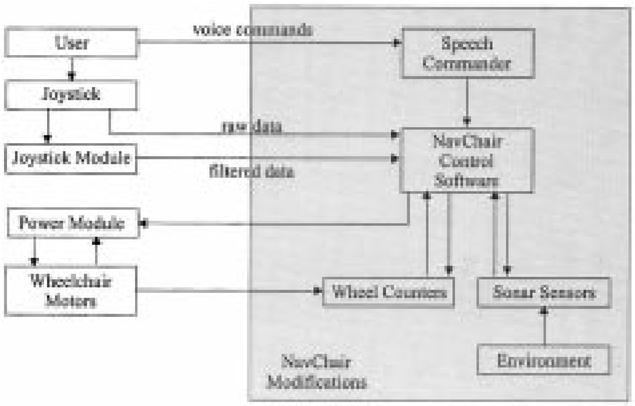

Fig. 1. Overview of the NavChair Assistive Wheelchair Navigation System.

Voice control is an attractive option for several reasons. Voice control systems can be used by any individual capable of consistent and distinguishable vocalizations; therefore, voice control is potentially appropriate for a large number of wheelchair users. Voice control would also reduce the physical requirements of operating a wheelchair. Finally, by eliminating the need to move one or more extremities to control the chair, voice control could assist the wheelchair operator in maintaining proper positioning within his or her seating system.

Unfortunately, voice control has proven difficult to implement within a standard power wheelchair. One difficulty is the very real possibility that a voice input system may fail to recognize a user's voice. Amori [1] dealt with this problem by limiting the amount of time that any command could move the chair, reasoning that momentary commands were less likely to produce collisions than latched commands. One drawback of this approach is the fact that even short-lived commands can cause collisions in a crowded area. McGuire [5], on the other hand, incorporated an external stop switch into his voice control system, but some users may lack the reflexes or coordination to activate a stop switch in time to avoid a collision. Another problem is the limited rate by which information can be transmitted by voice. An experienced voice recognition user can enter between 30 and 50 words per minute [3]. In practice, this makes voice input useful for general directional commands used in operating a wheelchair in open spaces but inadequate for rapid correctional maneuvers in crowded environments.

The challenge, then, is to implement a voice interface for a wheelchair that assures the safety of the wheelchair rider, remains unobtrusive (i.e., the voice interface must not require multiple corrective inputs from the user and must not use long or complex commands), and is easy to learn. To ease learning, the voice interface should consist of a small number of commands that are consistent and intuitive. In addition, safety requires that the voice control system must anticipate that commands may be misinterpreted or ignored and be impervious to extraneous noise.

The voice control system described in this paper was implemented within the NavChair Assistive Wheelchair Navigation System [4]. The NavChair is being developed to provide mobility to those individuals who would otherwise find it difficult or impossible to operate a power wheelchair. The NavChair was chosen for this project because the navigation assistance it provides to the user makes it possible to ensure the user's safety while limiting the amount of interaction required between the user and the wheelchair. The NavChair's navigation assistance allows the wheelchair operator to supply gross directional commands while the NavChair itself makes the numerous small corrective maneuvers actually needed to reach the target. Most important, the NavChair's obstacle-avoidance capability means that misinterpreted or ignored commands will not cause a collision.

TABLE I
LIST OF VOICE COMMANDS

Command	Description
Stop	The NavChair comes to an immediate halt.
Go Forward	The NavChair begins moving at a constant speed in the direction that the chair is facing.
Go Backward	The NavChair begins moving at a constant speed in the direction opposite to that which the chair is facing.
Soft Left	The NavChair makes a small (approximately 10 degree) left turn.
Hard Left	The NavChair makes a large (approximately 20 degree) left turn.
Rotate Left	The NavChair begins rotating (in place) to the left until the operator tells it to stop or move forward.
Soft Right	The NavChair makes a small (approximately 10 degree) right turn.
Hard Right	The NavChair makes a large (approximately 20 degree) right turn.
Rotate Right	The NavChair begins rotating (in place) to the right until the operator tells it to stop or move forward.

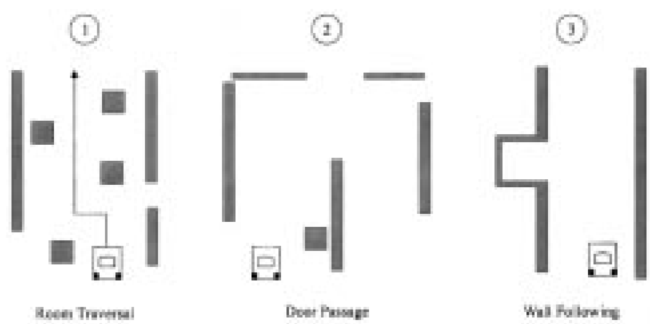

Fig. 2. Experimental tasks.

II. Voice Control Implementation

The NavChair prototype is based on an Everest and Jennings[1] Lancer power wheelchair augmented with an IBM-compatible 33-MHz 80 486-based computer and an array of 12 sonar sensors. All 12 sonar sensors are mounted on the lap tray and face to the front or side of the wheelchair. As shown in Fig. 1, during operation, the NavChair system interrupts the connection between the wheelchair's joystick and wheel motor controllers. The wheelchair operator uses voice commands to indicate the desired path of travel, and this information is combined with information about the wheelchair's immediate environment (from the sonar sensors) to identify a safe path of travel. The control signals that correspond to this path of travel are sent to the wheelchair motors, dictating the direction and velocity of the wheelchair.

The NavChair's voice control facility is based on the Verbex SpeechCommander,[2] a commercially available continuous-speech

[1]Everest and Jennings, Inc., 3601 Rider Trail South, Earth City, MO 63045 USA.

[2]Verbex Voice Systems, 275 Raritan Center Parkway, Edison, NJ 08837 USA.

TABLE II
LIST OF EXPERIMENTAL MEASURES

Experimental Measure	Measurement Method and Units
Average Time	Recorded by NavChair. Measured in seconds.
Average Speed	Value maintained by NavChair software. Measured in centimeters/second.
Average Minimum Obstacle Clearance	Recorded from sonar data by NavChair. Measured in centimeters.
Forward Noise	Recorded by NavChair. Root mean square average of the forward motor command over 10 Hz.
Steer Noise	Recorded by NavChair. Root mean square average of the steer motor command over 10 Hz.
Front Collisions	Recorded by experimenter.
Side Collisions	Recorded by experimenter.
Rear Collisions	Recorded by experimenter.

voice recognition system that relays user commands via a serial interface. Prior to operation, users train the SpeechCommander to identify a small set of commands, a process that is typically accomplished in less than 10 minutes. During operation, the user speaks a command into the SpeechCommander's microphone, worn on a headset. The SpeechCommander identifies the sound signal as one of the pretrained commands and transmits a computer code associated with that command to the NavChair's computer. The NavChair's computer matches the signal from the SpeechCommander to a specific joystick command which is then used to steer the chair.

Table I contains a list of the available voice commands. The number of commands was intentionally limited to decrease the amount of time necessary to train the speech recognition system to recognize each subject's voice and the amount of time needed to teach each subject the voice control commands.

III. Experimental Evaluation

Six able-bodied subjects (five male and one female), ranging in age from 22 to 26, participated in this experiment. All subjects had normal vision (although some wore corrective lenses), and none had any neurological impairment that affected their ability to operate a wheelchair.

During the experiment, subjects were asked to perform three tasks, shown in Fig. 2. Each task was first performed four times with navigation assistance active (condition WNA) and then four times without navigation assistance (condition NNA). The order of tasks was not counterbalanced across subjects, nor was the order of conditions (the NNA condition was always *second* to provide the greatest amount of practice possible with voice control). After the experiment was finished, subjects were asked to rate each condition from 1 (worst) to 10 (best).

During each trial, the performance measures listed in Table II were recorded. Most measures are self-explanatory, except forward and steer noise, which are quantitative measures of ride comfort measured as the root-mean-square (rms) average of the linear (forward noise) and angular (steer noise) motor commands exceeding 10 MHz. Larger noise values reflect greater changes in velocity and less "smooth" travel of the wheelchair. Data for all measures were compared using a two-level (WNA versus NNA) repeated-measures ANOVA with a repeated measure of trial for each experimental measure. Statistical significance was defined as a p-value less than 0.05.

IV. Results

Statistically significant differences between conditions are shown in Table III in bold. No performance measure had a significant effect for trial. WNA received an average ranking of 8.17 (out of 10) from subjects, while NNA received an average ranking of 4.67, a difference that was statistically significant. No subject failed to successfully complete any of the tasks on any of the trials under either condition.

The only significant difference between NNA and WNA in terms of average time or speed occurred during the door-passage task for average time. The difference was caused by navigation assistance stopping the chair as it approached the door and forcing the user to back up to reposition the chair. This slowed completion of the task but also reduced the number of collisions that occurred while passing through the doorway. Interestingly, although the WNA condition generally caused the NavChair to move slower and take more time to complete tasks, on the wall-following task (Task 3), the WNA condition actually allowed the chair to maintain a greater average speed and complete the task in less time by reducing the amount of corrective maneuvers required by the user.

Navigation assistance also contributed to making the ride more comfortable. There was a large and significant difference in the amount of steer noise between the two conditions for all three tasks. The only time a significant difference was noted for forward noise (in the door-passage task) was when WNA caused less forward noise than NNA did. Navigation assistance led to slightly more forward noise in the other tasks, but the difference was not significant.

Condition WNA was noticeably safer than condition NNA was in terms of collisions and average clearance. Significant differences were observed between conditions for front and side collisions during the door-passage task. In general, WNA kept a greater minimum

TABLE III
EXPERIMENTAL RESULTS. SIGNIFICANT DIFFERENCES SHOWN IN **BOLD**

Measure	Condition	Task 1	Task 2	Task 3
Average Time	WNA	11.0	**57.91**	18.10
	NNA	9.84	**37.55**	22.94
Average Speed	WNA	46.96	18.64	50.61
	NNA	53.72	26.92	45.29
Forward Noise	WNA	0.47	**0.33**	0.38
	NNA	0.34	**0.52**	0.28
Steer Noise	WNA	**1.06**	**0.62**	**0.85**
	NNA	**3.82**	**2.09**	**1.70**
Average Minimum Obstacle Clearance	WNA	56.62	62.20	44.71
	NNA	54.48	62.42	42.36
Front Collisions	WNA	0.00	**0.00**	0.00
	NNA	0.08	**0.33**	0.13
Rear Collisions	WNA	0.00	0.13	0.00
	NNA	0.00	0.08	0.00
Side Collisions	WNA	0.00	**0.00**	0.00
	NNA	0.00	**0.50**	0.29

distance from obstacles and had fewer collisions. Note that rear collisions did occur under the WNA condition in the door-passage task (Task 2) due to the lack of sonar sensors on the rear of the NavChair.

V. DISCUSSION

Based on users' subjective ratings alone, navigation assistance is clearly preferred when using voice control. Navigation assistance decreased the likelihood of a collision and reduced the amount of "noise" in the chair's travel. When there was no navigation assistance, collisions were typically caused by the voice recognition system's inability to correctly recognize a command or the subjects' inability to make rapid compensatory control inputs when navigating in confined areas.

Navigation assistance, on the other hand, allowed the NavChair to immediately compensate for misinterpreted commands. Navigation assistance also allowed the NavChair to automatically perform the small adjustments in speed and direction necessary to successfully pass through closely spaced obstacles, such as two doorposts. The approach that most users took to steer through doorways when navigation assistance was not active was to line the chair up with the door and drive straight at it, hoping to get through with, at most, one corrective maneuver.

It is certainly possible to implement voice control within a wheelchair that does not provide navigation assistance, but there are reasons to doubt the effectiveness of traditional approaches to ensuring user safety. For example, it is possible to reduce occasions where the system incorrectly recognizes (or fails to recognize) a command, but this possibility cannot be completely eliminated. In addition, informal observations of subject behavior would indicate that providing an external stop switch might not be particularly effective. During experiments, the NavChair was configured to move only when the joystick was displaced, meaning that a subject could bring the chair to an immediate halt by releasing the joystick. However, during training and actual experimentation, subjects were generally too engrossed with the task of steering to think of releasing the joystick prior to a collision.

An interface could also be developed that allowed users to make variable-degree turns, which would probably reduce the amount of jerkiness experienced by users. However, as the complexity of the voice interface increased, the number of subjects for whom it was appropriate would decrease. In addition, more complex commands would likely decrease the number of commands that could be given in a fixed amount of time.

Navigation assistance represents a viable design alternative that allows the voice interface to be simplified and helps to maintain the safety of the operator and the wheelchair. More important, we believe the results we observed apply equally well to other discrete wheelchair control methods. A set of switches is functionally equivalent to the set of voice commands used by subjects during this experiment, and it is likely that users of these wheelchair control methods would receive similar benefits from navigation assistance.

REFERENCES

[1] R. Amori, "VOCOMOTION—An intelligent voice-control system for powered wheelchairs," in *Proc. 15th Annu. RESNA Conf.* Toronto, Canada, 1992, pp. 421–423.
[2] J. Clark and R. Roemer, "Voice controlled wheelchair," *Arch. Physical Med. Rehab.*, vol. 58, pp. 169–175, 1977.
[3] D. Kambeyanda, S. Cronk, and L. Singer, "Potential problems with use of speech recognition products," in *Proc. RESNA'96 Conf.* Salt Lake City, UT, 1996, pp. 307–309.
[4] S. Levine, D. Bell, L. Jaros, R. Simpson, Y. Koren, and J. Borenstein, "The NavChair Assistive Wheelchair Navigation System," *IEEE Trans. Rehab. Eng.*, vol. 7, pp. 443–451, Dec. 1999.
[5] W. McGuire, "Voice operated wheelchair using digital signal processing technology," in *Proc. 22nd Annu. RESNA Conf.*, 1999, pp. 364–366.
[6] G. Miller, T. Brown, and W. Randolph, "Voice controller for wheelchairs," *Med. Biol. Eng. Comput.*, vol. 23, pp. 597–600, 1985.