Presented at the 1995 International Joint Conference on Artificial Intelligence (IJCAI), Summer '95.

The NavChair Assistive Navigation System

Richard Simpson[1,3], Simon P. Levine[1,3], David A. Bell[2,3]

Yoram Koren[2,3], Johann Borenstein[2], and Lincoln A. Jaros[1]

[1]Rehabilitation Engineering Program, Department of Physical Medicine and Rehabilitation

[2]Department of Mechanical Engineering

[3]Graduate Bioengineering Program

University of Michigan

ABSTRACT

The NavChair assistive navigation system is being developed to increase the mobility of severely handicapped individuals by providing navigation assistance for a power wheelchair. During the course of developing NavChair, advances have not only been made in the technology of "smart wheelchairs," but in other areas as well. Work on the NavChair has prompted the development of an obstacle avoidance method, based on an algorithm originally designed for autonomous robots, which allows the NavChair to perform otherwise unmanageable tasks and forms the basis of an adaptive controller. A method of modeling the wheelchair operator to make control adaptation decisions has also been developed and experimentally validated as part of the research on the NavChair. This paper details this past work on the NavChair (along with experimental validation) and also presents work that is to come, which is intended to increase the versatility and functionality of the NavChair.

INTRODUCTION

The NavChair assistive navigation system (Levine, et al, 1990) is being developed to provide mobility to those individuals who would otherwise find it difficult or impossible to use a powered wheelchair due to cognitive, perceptual or motor impairments. By sharing vehicle control decisions regarding obstacle avoidance, safe object approach, maintenance of a straight path, etc., it is hoped that the motor and cognitive effort of operating a wheelchair can be reduced.

The variety of abilities and needs of wheelchair users is very great. If a "smart wheelchair" such as the NavChair is to accommodate this diversity, it must be capable of responding to many different operating requirements, across users and even across a single room. The NavChair is thus being built to provide navigation assistance in the form of a hierarchy of operating levels, each of which requires varying degrees of control from a wheelchair user.

The NavChair currently operates within one level of the hierarchy, where the user controls the path of navigation and the wheelchair's motion along that path, and the NavChair restricts itself to ensuring collision-free travel. At this level, the NavChair offers several different modes of operation: general obstacle avoidance, door passage assistance, and close approach to an object. This operating level works well with continuous input methods such as a joystick but is less suited to discrete methods such as voice control. A level requiring additional control from the NavChair system is appropriate when using voice to operate the NavChair and the system must make some (or all) of the path planning decisions. At an even higher level of the hierarchy, the user would supply the target and the system would plan the path completely.

This paper will discuss the development of NavChair in pursuit of this goal and how we plan to approach the work that remains to be done.

THE NAVCHAIR'S HARDWARE

The hardware components of the NavChair have been described elsewhere (Jaros, et al, 1993) and will only be summarized here. The NavChair prototype is based on a standard Lancer powered wheelchair from Everest & Jennings. The Lancer's controller is divided into two components: the joystick module, which receives input from the user via the joystick and converts it to a signal representing desired direction, and the power module, which converts the output of the joystick module to a control signal for the left and right wheel motors. Originally, the user's joystick input was obtained in the form of output from the joystick module. However, the joystick module performs smoothing and filtering operations, which can obscure the user's original input. For this reason, the NavChair now receives the "raw" joystick data and incorporates the Lancer joystick module's filtering and smoothing operations into its software after the navigation assistance calculations have been performed.

The components of the NavChair system are attached to the Lancer and receive power from the chair's batteries. The NavChair system consists of three units: (1) an IBM-compatible 33MHz 80486-based computer, (2) an array of 12 Polaroid ultrasonic transducers mounted on the front of a standard wheelchair lap tray, and (3) an interface module which provides the necessary interface circuits for the system. During operation the NavChair system interrupts the connection between the joystick module and the power module. The joystick position (representing the user's desired trajectory) and the readings from the sonar sensors (reflecting the wheelchair's immediate environment) are used to determine the control signals sent to the power module.

Sonar sensors are used because of their operational simplicity and low cost. However, individual sonar readings are often erroneous. A method used to reduce these errors and create a sonar map of the chair's surroundings is called the Error Eliminating Rapid Ultrasonic Firing (EERUF) method (Borenstein & Koren, 1992). The accuracy of the map is further enhanced by keeping track of the wheelchair's motion via the wheel rotation sensors built into the Lancer's wheel motors. The result is a sonar map that is surprisingly accurate given the constraints of individual sonar sensors.

NAVIGATION ASSISTANCE

VFH - Obstacle Avoidance Based on Mobile Robotics

The original obstacle avoidance technique used in the NavChair**,** the Vector Field Histogram method (VFH) (Borenstein & Koren, 1989; Borenstein & Koren, 1991), was derived from work in autonomous mobile robotics. Briefly, the VFH algorithm (see Figure 1) can be described as follows:

1. Input from the sonar sensors and wheel motion sensors is used to update a Cartesian map centered around the chair. The map is divided into small blocks, each of which contains a count of the number of times a reading has placed an object within that block. The count within each block represents a certainty value that an object is within that block, thus the more often an object is seen within a block the higher its value.
2. The two-dimensional grid map is converted into a polar histogram, centered on the vehicle that maps obstacle density (a combined measure of the certainty of an object being within each sector of the histogram and the nearness of that object) verses different directions of travel.
3. The polar histogram is searched for a direction of travel that is as close as possible to the target direction indicated by the user, while also having an obstacle density beneath a predetermined safety threshold.
4. The direction chosen is then modified further by virtual repulsive forces from all objects in the Cartesian grid. The virtual force is calculated based on the distance of each object so that nearby obstacles repel the NavChair more than distant objects.

MVFH - An Obstacle Avoidance Method for Shared Control Systems

During development of the NavChair, it was discovered that several modifications to the original VFH method were required, in order for VFH to make the transition from autonomous mobile robots to wheelchairs. VFH was not particularly well suited to the shape of a wheelchair or the comfort requirements of a human operator. In addition, VFH was incapable of supporting all of the desired operating modes.

One difficulty in applying an obstacle avoidance routine developed for a robot to a wheelchair is the different shapes of the two platforms. Mobile robots in general (and those VFH was originally intended for in particular) are round**,** which simplifies the calculation of trajectories and collision avoidance. While VFH has been applied to "non-point" mobile robots similar in nature to a wheelchair (Borenstein & Raschke, 1991) it was determined that VFH could not support all of the desired operating modes (door passage in particular) while also ensuring the safety of the operator and vehicle during operation.

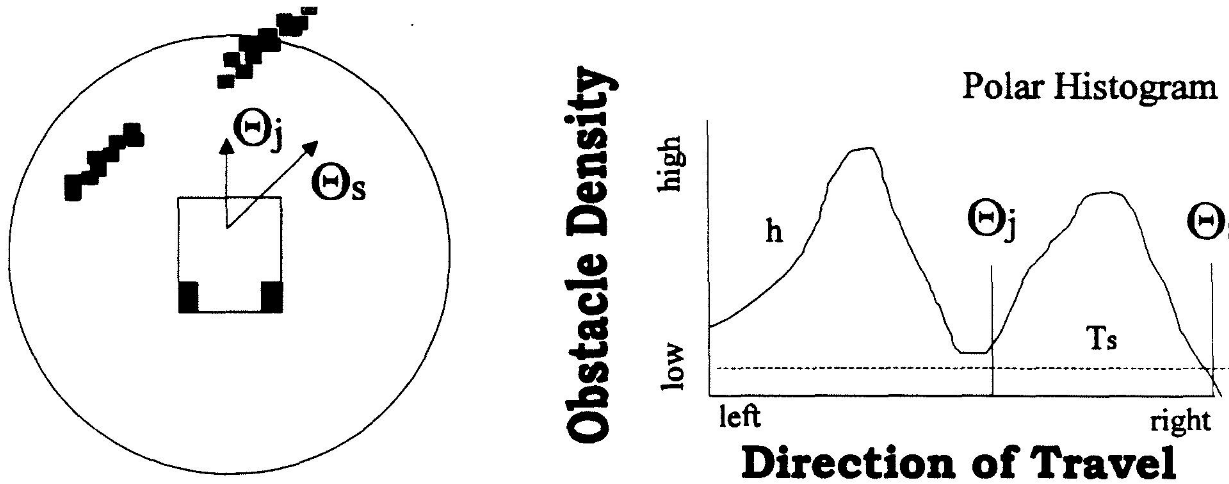

Figure 1: VFH obstacle avoidance. The left figure shows the certainty grid around the NavChair; the right figure shows the polar histogram at the same instant, where: Θ_j is the desired direction of travel, as indicated by the user with the joystick; h is the polar histogram representing obstacle densities in each possible direction of travel; T_s is the safety threshold value; Θ_s is the safe direction of travel selected by VFH. (Borenstein & Koren, 1989).

Another problem arose from what is considered one of the VFH method's greatest strengths, the ability to move through a crowded environment with a minimal reduction in speed. While this is acceptable for an autonomous robot, it can result in abrupt changes in direction which a wheelchair operator is likely to consider “jerky” and unpredictable behavior. Thus, an algorithm which provided more intuitive control was deemed necessary.

In response to these needs, the Minimal VFH (MVFH) method was developed (Bell, et al, 1994a; Bell et al., 1994b). MVFH also proceeds in four steps (see Figure 2), the first two of which are identical to VFH. However, in the third step of the process, instead of searching for a direction of travel near to the desired direction of travel, a weighting function (curve "w" in Figure 2) is added to the polar histogram (curve "h"), and the direction of travel with the resulting minimal weighted obstacle density (Θ_s) is chosen. As seen in Figure 2, the weighting function is a parabola with its minimum at the direction of travel indicated by the wheelchair's joystick position. Thus, the direction indicated by the user's input from the joystick receives the least amount of additional weight (obstacle density) and those directions furthest from the user's goal receive the most weighting, which predisposes the chair to pursue a direction close to the user's goal.

In the fourth step, the wheelchair's speed is determined based on the proximity of obstacles to the projected path of the chair. This step models the shape of the wheelchair exactly, which allows the chair to approach objects more closely than VFH while still maintaining the safety of the vehicle.

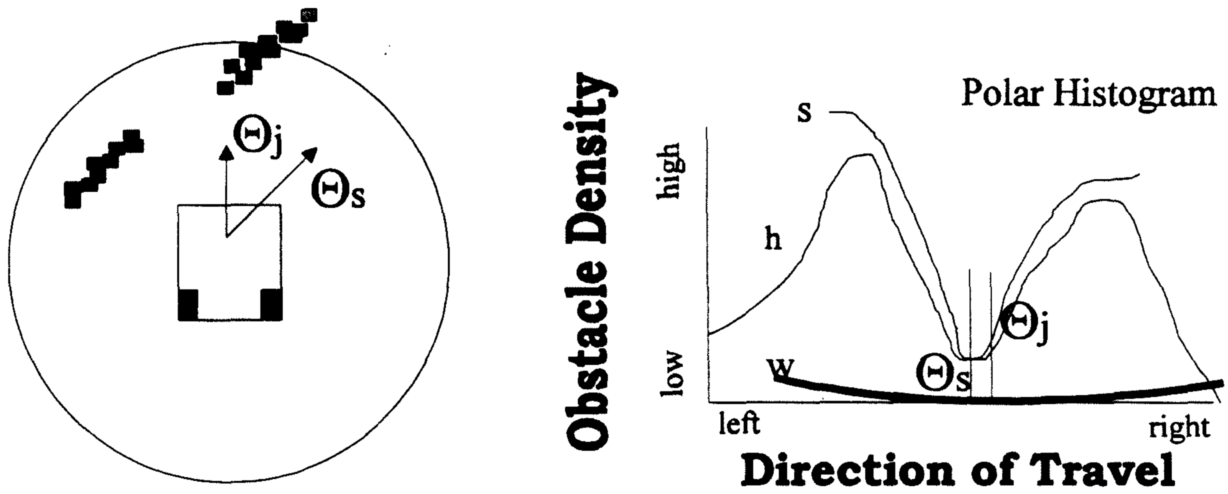

Figure 2: MVFH obstacle avoidance. The left figure shows the certainty grid around the NavChair; the right figure shows the polar histogram at the same instant, where: Θ_j is the desired direction of travel, as indicated by the user with the joystick; h is the polar histogram representing obstacle densities in each possible direction of travel; w is the weighting function symmetrical about the desired direction of travel (Θ_S), s is the sum of h and w; Θ_s is the actual direction of travel selected by MVFH at the minimum of s. (Bell, 1994)

Experimental Validation of MVFH

Five tests were run, which compared the performance of VFH, MVFH, and an experienced wheelchair operator using the unmodified wheelchair control system (Bell, 1994). The tests were performed in a u-shaped hallway with two right-angle turns containing difficult situations typical of modern office buildings: mixed smooth tile and rougher concrete walls, a section of glasswall, and narrow doorways. The test course was approximately 2 meters wide and 30 meters long. In all tests, four quantitative measures of performance were collected to be used as the basis of comparison: average speed (m/s), jerkiness (RMS average of the portion of the motor command above 10 Hz), average obstacle clearance (measured from the side of the wheelchair), and risk of a collision (collisions and near misses per second). For both obstacle avoidance methods, the system was configured to produce optimal system performance as measured by the above variables.

The first two tests evaluated VFH obstacle avoidance. In Test 1 the user was blindfolded and traversed the course by holding the joystick towards the wall, at approximately a 45° angle, while in Test 2 the user was able to see the course and attempted to steer the chair straight down the middle of the hallway. Tests 3 and 4 measured the performance of MVFH but were otherwise exactly the same. In the fifth test, an experienced user traversed the course as quickly as possible without navigation assistance.

Table 1 presents the results of the experiment. Notice that MVFH performs as well as or better than VFH in terms of every performance measure. In particular, MVFH is as fast as VFH while providing smoother travel.

There are several other advantages of MVFH not brought out by the experimental results which deserve mention. First and foremost, using MVFH, control of the chair becomes much more intuitive and responsive. Small changes of the joystick position result in changes in the wheelchair. Second, by modeling the exact shape of the NavChair it is possible to perform previously unmanageable tasks, such as passing through doorways. Most importantly, however, MVFH provides an adaptable level of navigation assistance. By changing the shape of the weighting function, MVFH can assume more or less control over travel decisions. This flexibility is crucial for our work on adaptive shared control of the NavChair.

Table 1: MVFH vs. VFH in the hallway environment. Four measures of performance are compared for a blindfolded user using obstacle avoidance and an expert user in the smooth hallway course. These results indicate that the blindfolded user is able to travel safely at about half the speed of the experienced user traveling without obstacle avoidance. MVFH slightly outperformed VFH, although the difference was not significant. (Bell, 1994)**.**

	VFH		MVFH		Experienced User
Hallway test number	test 1	test 2	test 3	test 4	test 5
speed (m/s)	0.73	0.78	0.77	0.78	1.62
clearance (m)	0.44	n/a	0.45	n/a	n/a
jerkiness	0.95	0.68	0.58	0.55	n/a
collisions	0	0	0	0	0

STIMULUS RESPONSE MODELING - ADAPTIVE SHARED CONTROL

During the design of the NavChair system it became clear that in order to provide the full range of functionality that was desired it would be necessary to define several different operating modes (Bell, et al, 1993). The operating modes that have been developed thus far are: General obstacle avoidance, close approach, and door passage.

Obstacle avoidance mode is intended for use within rooms or hallways to provide fast, collision-free travel. When the NavChair is in this mode, the maximum speed of the chair is greater, and the distance within which the chair is allowed to approach an object is kept higher, than other modes. Close-approach allows the user to "dock" the wheelchair at an object (a desk or a table, for example), whereas door passage mode is designed to let the user steer the NavChair through doorways. In both of these modes, the maximum speed of the chair and minimum approach distance are both reduced. It was the implementation of these two modes, which were not possible using VFH, that drove the development of the MVFH method.

Once these different operating modes were developed, their presence created a need for a method of determining the most appropriate operating mode. One conceivable solution was to require the user' to manually manage the task of mode determination. While this would work well for some users, it would place unacceptable performance burdens on others. Thus, a method of implicitly identifying the correct operating mode from the user's control actions, called Stimulus Response Modeling (SRM) (Bell, 1994; Bell, et al, 1993), was developed.

Essentially, SRM observes the user's responses to known stimuli and classifies those responses based on models of behavior as a function of different possible user intentions. The stimuli can either be naturally occurring or can be generated by the system itself. In the case of the NavChair, a stimulus was generated by the control software and applied as a slight offset to the user's joystick input. If the user's response to these permutations was a coherent attempt to override them, coherent being defined as identifiable by a performance model, then the NavChair switched to a more appropriate mode.

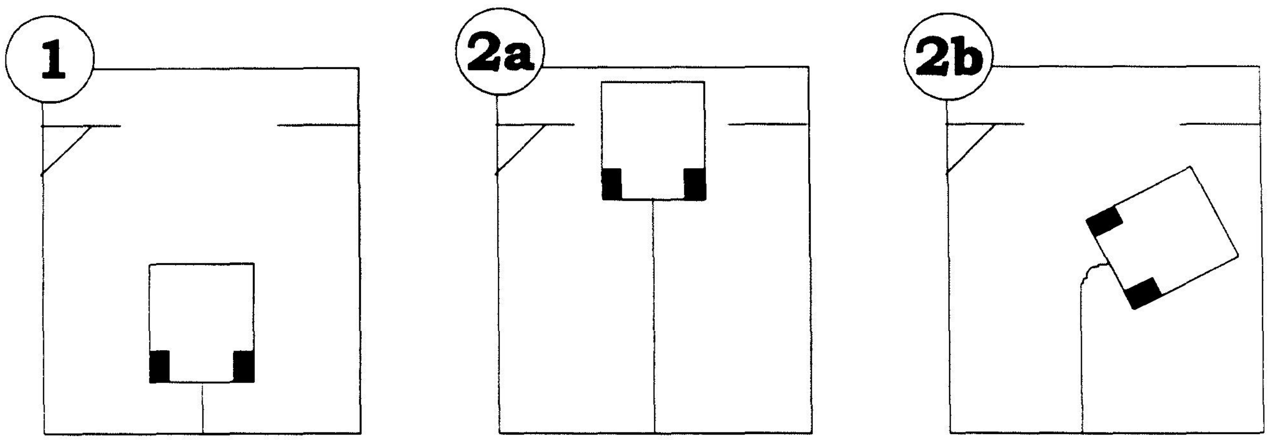

Figure 2: Door passage experiment. Frame (1) shows the NavChair approaching an asymmetrical doorway. Obstacle avoidance and door passage modes produce entirely different behaviors: (2a) door passage mode centers the NavChair in the doorway and allows it to pass, or (2b) obstacle avoidance slows and steers the NavChair to avoid the wall in its path, preventing successful door passage.

Experimental Validation of SRM

A variety of experiments have been conducted to verify the efficacy of SRM for human-machine system adaptation (Bell, 1994). Only those which deal explicitly with the NavChair will be presented here, the interested reader is directed to (Bell, 1994) for further discussion of SRM.

A method of choosing between general obstacle avoidance and door passage modes based on

SRM was developed and evaluated. In experiment one, the accuracy and timing of mode changes was examined. In the remaining experiments, system performance using automatic mode selection was compared to performance using only one mode (general obstacle avoidance in experiment two and door passage mode in experiment three).

In the first experiment, the timing and accuracy of mode selection was examined using the same experimental setup as the second experiment (see Figure 3). As can be seen from Table 2, mode selection was performed correctly in every test, and the average door passage success rate is consistent with the results achieved in the previous experiment. Mode selection happened an average of almost 3 seconds before the NavChair entered the doorway.

The second experiment conducted compared the performance of general obstacle avoidance with and without automatic mode selection. The protocol used was similar to the hallway test outlined earlier. The course was identical, but the subjects were not blindfolded and only MVFH obstacle avoidance was used. As can be seen from Table 3, the performance of the NavChair was only slightly reduced with automatic mode selection active.

Table 2: Mode selection test. Mode transition time measures the time from the mode transition to when the front of the chair entered the doorway. Average speed refers to the entire door passage maneuver. The mode selection rate is the percentage of correct door passage mode selections. Door passage rate is the number of successful door passages as a percentage of attempts. (Bell, 1994).

	S1	S2	S3	S4	S5	Mean	Std. Dev.
Mode Transition Time(s)	2.91	2.10	*2.55*	2.85	*2.53*	*2.59*	0.32
Average Speed (m/s)	0.20	0.26	0.22	0.19	0.21	0.22	0.03
Mode Selection Success (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Door Passage Success (%)	90.00	100.00	90.00	80.00	100.00	92.00	8.37

The experimental setup for the third experiment was the same as in experiment one and is shown in Figure 3. This experiment evaluated the NavChair's ability to pass through doorways with automatic mode selection active versus with automatic mode selection inactive and the chair "locked" in door passage mode. As can be seen from Figure 4, there was not a significant change in performance observed. However, the subjective difficulty, as reported by test participants. did increase with the addition of automatic mode selection.

Table 3: Results of hallway test. These results compare the performance of the NavChair in obstacle avoidance mode and under automatic mode selection. The purpose of this experiment was to determine how much automatic mode selection reduced the performance of obstacle avoidance. The primary results was of no statistically significant difference, although the measured performance was better for all measures under non-adaptive obstacle avoidance. One interesting result is that mode selection appears to have increased the variability of all performance measures.

	MVFH alone		MVFH with automatic mode selection	
Performance Measures	mean	std. dev.	mean	std. dev.
Time (s)	41.3	3.19	41.7	3.46
Average Speed (mm/s)	703	44.7	682	58.2
Jerkiness forward)	0.26	0.07	0.32	0.14
Jerkiness (side)	0.72	0.06	0.63	0.12
Distance to Wall	480	48.3	483	61.4

Automatic mode selection is crucial for the NavChair. The NavChair is not capable of passing through doorways in obstacle avoidance mode, and the chair moves too slow in door passage mode for use in general travel. Thus, both modes (and a means of automatically switching between them) are necessary for the NavChair to achieve full functionality. These experiments show that SRM can perform this task quickly enough and without a significant drop in performance.

A Proposed Enhanced Method for Adaptive Shared Control

Previous sections have discussed work that has already been completed. The sections that follow detail proposed future directions of work on the NavChair, beginning with a method for adaptive shared control which will hopefully represent an enhancement of the functionality of SRM.

A limitation of SRM is that it does not make use of all of the information available to it. In the case of the NavChair, it focuses exclusively on the user's control actions and ignores the immediate environment of the chair. SRM is a purely *reactive* method of machine adaptation. It responds to what the user is doing at the moment and considers those actions against all of the possible goals that the user could have. A more robust system would be both reactive and *predictive,* using cues within the environment to constrain the possible goals that a person could have, which the reactive system could then choose from.

More importantly for our purposes, future goals of the NavChair are not compatible with the current state of development of SRM-based adaptation. SRM was developed and tested with the NavChair operating at a fixed range of automation and using a fixed input method joystick). What

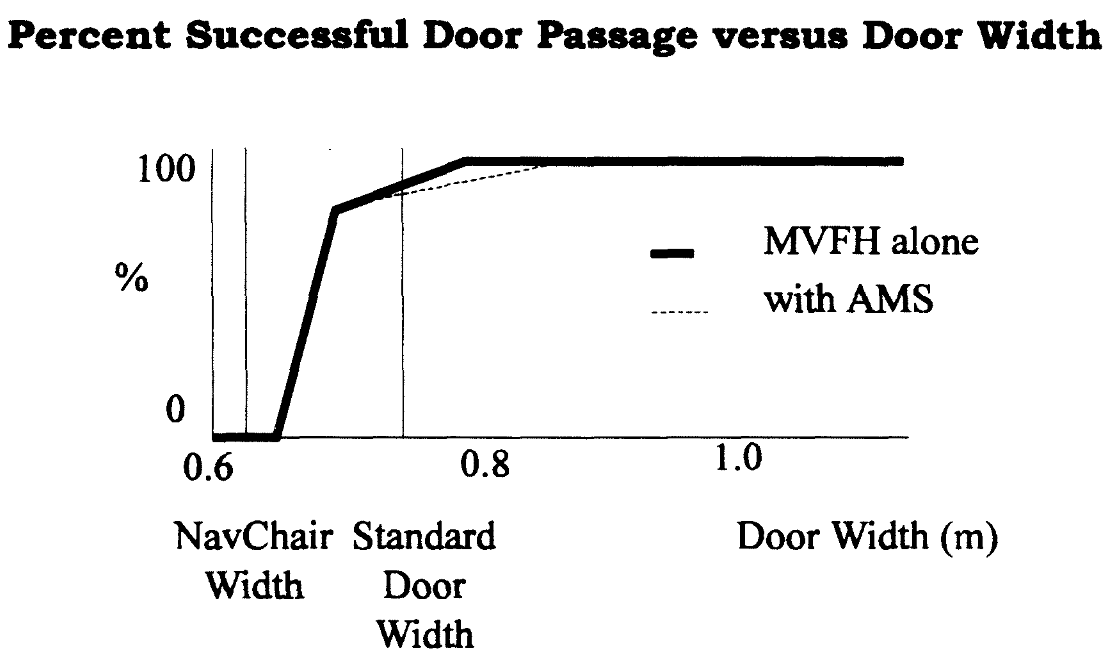

Figure 3: Results of door passage test. This graph compares MVFH door passage mode (thick solid line) with the adaptive mode (dashed line), showing no significant change in door passage performance. (Bell, 1994).

is ultimately desired is an adaptation method capable of managing adaptation in the hierarchy of automation, from almost fully automatic to almost fully manual, and also allowing a variety of different input methods, from voice to pneumatic switches. In response to these increased demands, a method of human-machine adaptation has been proposed which draws on work in several different areas of Artificial Intelligence, including probabilistic reasoning and neural networks.

In pursuit of additional information relevant for adaptation in the NavChair, we have examined the use of Neural Networks to identify important cues within the environment (Simpson, et al, 1994). We have successfully trained a three-layer back-propagation algorithm to identify walls and corners based on input from the NavChair's sonar sensors. The neural networks were small enough that, once trained, could classify sonar input quickly enough to be incorporated into a real-time mode adaptation scheme.

We have also implemented a simulator, which uses a Bayesian Net (Charniak, 1991; Pearl, 1988) and environmental information to make predictions about the user's intentions. While the simulator represented a gross simplification of the NavChair in operation, its success in predicting user intentions provides initial support for the applicability of our method. While adaptation based strictly on environmental sensing is not likely to be successful under all of NavChair's operating conditions (Bell, 1994), it is likely that environmental information can be used as a predictive indicator to constrain the choice of possible user goals, which will be made by a reactive method such as SRM. We have focused our attention on the use of Bayesian Networks, which are flexible enough to make use of additional information available in the NavChair. What is envisioned is a network that can make use of both predictive and reactive information from a variety of sources in order to determine the user's goal. Once the user's intentions are known, the system can be adapted to provide optimal performance.

Other Future Plans

Besides implementing the above adaptation scheme, there are other changes in store for the NavChair, many of which will also draw on existent Artificial Intelligence techniques. The overriding goal is, of course, to make the NavChair as useful as possible to as many people as possible. With this in mind, the most helpful immediate change will be to expand the number of input methods that the NavChair can accept. We would like to allow a user the option of an analog joystick, a switch-based control method (switch joystick, pneumatic switches, head switches, etc.), and even voice control.

However, these different input methods will require different operating modes and levels of aiding from the NavChair. For example, voice is much less suited to providing the continuous tracking input required by the NavChair's current operating modes (Wickens, 1992). A higher-level of the function hierarchy presented in the beginning of this paper, which allows the user to specify a target at the beginning of motion and requires little other input, would be more appropriate in this case'. Of course, a joystick user might also benefit from such an operating mode as well. Thus, the effort to increase the control options of the chair will drive the development of further elements of the hierarchy. Part of the groundwork for this effort will be the development of an internal mapping system for the NavChair, which will draw on existing work in robot planning and environmental mapping.

One problem of trying to follow a map with a robot is the error caused by inaccurate dead-reckoning. Due to the limitations of a wheelchair's dynamics and current sensors, accurate long-distance dead-reckoning in the NavChair is next to impossible. For this reason, we plan to rely on topological maps (Kuipers, 1978), which reflect the connections between different areas of the map without encoding metric distance measurements. Because navigation in a topological map is point-to-point, it is not possible for errors in navigation to accumulate over the course of navigating a long path. The particular topological mapping scheme we have been investigating was developed here at the University of Michigan and is known as Prototypes, Location and Associative Networks (PLAN) (Kortenkamp & Weymouth, 1994).

Another difficulty encountered when attempting to use a map is that of localization, determining exactly where on the map the robot is and what its orientation is. Performing localization automatically, will be difficult because topological maps by their nature provide less detail that can be used for this process than a metric map and sonar sensors provide limited information. We intend to circumnavigate this problem with the help of the user. Because we have a human operator on board at all times we can rely on that person to provide the NavChair with the information that it cannot ascertain on its own.

CONCLUSION

This paper has provided an overview of the NavChair system: past, present, and the envisioned future. Early work focused on the application of obstacle avoidance techniques originally developed for autonomous mobile robots to a wheelchair. Initial success led to modifications of the obstacle avoidance technique to make it more suitable for human-machine Systems and to allow the development of different operating modes to expand the original functionality of the system. The presence of multiple operating modes created a need for a method of automatically identifying the correct operating mode based on the control inputs of the user. The future work planned for the NavChair is aimed at adding to its potential user population by further increasing its functionality. New methods of input and accompanying levels of automation are envisioned as is an enhanced method of choosing between operating modes based on probabilistic reasoning.

REFERENCES

[1] Bell, D. (1994). *Modeling Human Behavior For Adaptation in Human Machine Systems.* Ph.D. Thesis, University of Michigan.

[2] Bell, D.A., Levine, S.P. Koren, Y., Jaros, L.A. & Borenstein, J. (1993). Shared Control of the NavChair Obstacle Avoiding Wheelchair. *In the Proceedings of the RESNA International Conference.* Washington, D.C.: RESNA, 370-372.

[3] Bell D.A., Levine, S.P., Koren, Y., Jaros, L.A. & Borenstein, J. (1994a). Design Criteria for Obstacle Avoidance in a Shared-Control System. In the *Proceedings of the RESNA International Conference.* Washington, D.C.: RESNA, 581-583.

[4] Bell, D.A., Levine, S.P., Koren, Y., Jaros, L.A., & Borenstein, J. (1994b). An Assistive Navigation System for Wheelchairs Based upon Mobile Robot Obstacle Avoidance. In the

Proceedings of the IEEE International Conference on Robotics and Automation. New York: IEEE Press.

[5] Borenstein, J. & Koren, Y. (1989). The Vector Field Histogram - Fast Obstacle Avoidance for Mobile Robots. *IEEE Journal of Robotics and Automation, 7(3).*

[6] Borenstein, J. & Koren, Y. (1991). Histogramic In-motion Mapping for Mobile Robot Obstacle Avoidance. *!EEE Transactions on Robotics and Automation, 17(4),* 535-539.

[7) Borenstein, J. & Koren, Y. (1992). Noise Rejection for Ultrasonic Sensors in Mobile Robot Applications. In the *Proceedings of the IEEE Conference on Robotics and Automation.* New York: IEEE Press, 1727-1732.

[8] Borenstein, J. & Raschke, U. (1991). Real-time Obstacle Avoidance for Non-Point Mobile Robots. In the *Proceedings of the Fourth World Conference on Robotics Research,* Pittsburgh, PA.

[9] Charniak, E. (1991). Bayesian Networks Without Tears. *Al Magazine, 12(4),* 50-63.

[10]Chown, E., Kaplan, S., & Kortenkamp, D. (1994). Prototypes, location, and associative networks (PLAN): Towards a unified theory of cognitive mapping. To appear in *The Journal of Cognitive Science*, 1994.

[1 l] Jaros, L., Bell, D., Levine, S., & Borenstein, Y. (1993). NavChair: Design of an Assistive Navigation System for Wheelchairs. In the *Proceedings of the 16th Annual RESNA International Conference*. Washington, D.C.: RESNA, 379-381.

[12] Kuipers, B.J. (1978). Modeling spatial knowledge. *Cognitive Science, 2(2),* 1978.

[13] Levine, S. P., Bell, DA., & Koren, Y. (1994). NavChair: An Example of a Shared-Control System *for* Assistive Technologies. In the *Proceedings of the 4th International Conference of Computer for Handicapped Persons*. Vienna, Austria.

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

[15] Pearl, J. (1988). *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference.* San Francisco, CA: Morgan Kaufmann.

[16] Simpson, R., Levine, S.P., Bell, D.A., & Jaros, L.A. (1994). The applicability of neural networks in an autonomous mode selection system. In the *Proceedings of the RESNA International Conference.* Washington, D.C.: RESNA, 578-580.

[17] Wickens, D.W. (1992). *Engineering Psychology and Human Performance.* Boston: Scott Foresman and Company.