The NavChair Assistive Wheelchair Navigation System

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Abstract*—The NavChair Assistive Wheelchair Navigation System [19] is being developed to reduce the cognitive and physical requirements of operating a power wheelchair for people with wide ranging impairments that limit their access to powered mobility. The NavChair is based on a commercial wheelchair system with the addition of a DOS-based computer system, ultrasonic sensors, and an interface module interposed between the joystick and power module of the wheelchair. The obstacle avoidance routines used by the NavChair in conjunction with the ultrasonic sensors are modifications of methods originally used in mobile robotics research. The NavChair currently employs three operating modes: general obstacle avoidance, door passage, and automatic wall following. Results from performance testing of these three operating modes demonstrate their functionality. In additional to advancing the technology of *smart wheelchairs*, the NavChair has application to the development and testing of "shared control" systems where a human and machine share control of a system and the machine can automatically adapt to human behaviors.

***Index Terms*— Obstacle avoidance, power wheelchairs, smart wheelchairs, wheelchair control, wheelchair navigation.**

I. INTRODUCTION

THE NavChair Assistive Wheelchair Navigation System [19], shown in Fig. 1, is being developed to provide mobility to individuals who would otherwise find it difficult or impossible to use a powered wheelchair due to motor, sensory, perceptual, or cognitive impairments. The NavChair shares vehicle control decisions with the wheelchair operator regarding obstacle avoidance, safe object approach, maintenance of a straight path, and other navigational issues, to reduce the motor and cognitive requirements for operating a power wheelchair.

The NavChair's broad range of potential users possess a very large variety of abilities and needs. If a "smart wheelchair" such as the NavChair is to accommodate this diversity, it must be capable of responding to many different operating requirements. 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 the wheelchair user.

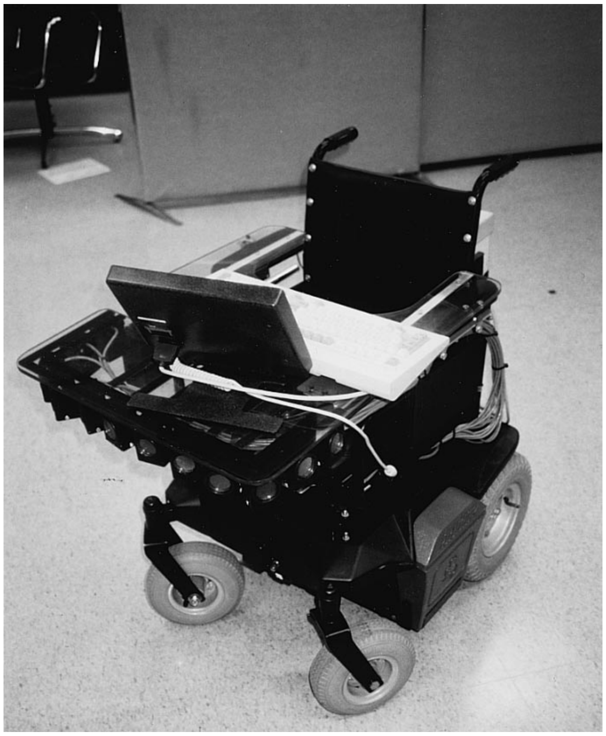

Fig. 1. Prototype of the NavChair assistive wheelchair navigation system.

At one level of the hierarchy the user is responsible for path-planning and most of the navigational responsibilities while the NavChair restricts itself to minor navigational responsibilities and collision-avoidance. This operating level works well with continuous input methods such as a joystick but is less suited to discrete methods such as voice control. Examples of users who might benefit from this level of assistance would include those with quadriplegia or quadripareses resulting from spinal cord injury, neuromuscular disease, or cerebral palsey, as well as those with cognitive or perceptual impairments resulting from brain injury, stroke, congenital conditions, etc. A second level, requiring additional control from the NavChair system, is appropriate when voice control or another discrete control method is used to operate the NavChair and the system must make some of the path planning decisions. This level of assistance might be appropriate for those with more severe motor impairments (i.e., very high level spinal cord injury or more severe cerebral palsey, brain injury, stroke, neuromuscular

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disease, etc.). An even higher level of the hierarchy is needed when the user supplies the target destination and the NavChair completely plans the path and navigates to the destination. A good example of a user requiring this level of assistance would be a person with a motor impairment requiring powered mobility who is also blind. The main focus of this paper is on the first level of operation for continuous input methods.

The goal in developing the NavChair is to try to provide the user with an appropriate level of navigation assistance that allows them to independently operate a powered wheelchair. In working to achieve this goal every attempt is also made to provide the highest level of performance possible. In practice this can be determining by how close NavChair can come to the performance of a "fully capable user" using a standard power wheelchair.

II. BACKGROUND

To date, prototypes of several smart wheelchairs have been developed, but none has made the transition to a commercial product. Two North American companies, KIPR[1] and Applied AI,[2] sell smart wheelchair prototypes for use by researchers, but neither system is intended for use outside of a research lab. The CALL Center of the University of Edinburgh, Scotland, has described the use of a wheelchair with bump sensors and the ability to follow tape tracks on the floor as part of a wheeled-mobility training program [22], but they have yet to produce a commercial product from their work.

The majority of smart wheelchairs represent outgrowths of mobile robotics research. The NavChair, for example, began as an application of the VFH [6], [7] and VFF [6] obstacle avoidance routines developed by Borenstein and Koren. The Wheelesly and TAO [13] smart wheelchairs are examples of subsumption-based systems [11] originally developed by Brooks. The University of Texas smart wheelchair [14] is an application of Kuiper's Spatial Semantic Hierarchy [18].

One useful way to classify smart wheelchairs is based on how they allocate control between the wheelchair operator and the wheelchair itself. Some smart wheelchairs [12], [24], [22], [28], [30] operate in a manner very similar to autonomous robots, the user gives the wheelchair a final destination and supervises as the chair plans and executes a path to the target location. To reach their destination, these systems typically require either a complete map of the area through which they navigate or some sort of modifications to their environment (e.g., tape tracks placed on the floor or markers placed on the walls), and are usually unable to compensate for unplanned obstacles or travel in unknown areas. Smart wheelchairs in this category are most appropriate for users who 1) lack the ability to plan and/or execute a path to a destination and 2) spend the majority of their time within the same controlled environment.

Other smart wheelchairs confine their assistance to collision avoidance, and leave the majority of planning and navigation duties to the wheelchair user [21], [19], [26], [29]. These systems do not normally require prior knowledge of an area or any specific alterations to the environment. They do, however, require more planning and continuous effort on the part of the wheelchair user and are only appropriate for users who can effectively plan and execute a path to a destination. Finally, a third group of smart wheelchairs offers both autonomous and semi-autonomous navigation [10], [13], [15], [17].

Another useful method of distinguishing smart wheelchairs is based on whether or not a given wheelchair offers multiple configurations (or operating modes), each designed for a specific set of tasks and input methods. For example, the NavChair offers three distinct operating modes for 1) traversing a room while avoiding obstacles, 2) passing through doorways, and 3) following a wall down a hallway. Other smart wheelchairs that offer task specific behaviors [10], [13], [15], [29] are able to accommodate a wider range of needs and abilities but present the added requirement of selecting the most appropriate configuration for a given task.

The responsibility for selecting the most appropriate operating mode can be performed by the user (manual adaptation to changing task requirements) or the smart wheelchair (automatic adaptation). The TinMan wheelchair [20] provides an example of manual adaptation. Users can change the setting of a dial to specify the amount of obstacle avoidance assistance provided by the wheelchair. On the other hand, the NavChair (as described in a companion paper—[25]) and the TAO systems [13], use automatic adaptation. The NavChair uses probabilistic reasoning techniques to combine information from the sonar sensors and a topological map to make adaptation decisions, while the TAO system's subsumptive reasoning approach allows the most appropriate behavior to emerge from a collection of potential behaviors.

The NavChair incorporates a combination of several innovative features that distinguish it from the other smart wheelchair systems described above. Unlike many of the systems, the NavChair is designed to function as a shared control system with an obstacle avoidance algorithm specifically developed to meet the vehicle's shared control needs and permit the NavChair to dynamically allocate control of the wheelchair based on current task demands. The NavChair also provides several operating modes to allow users with varying abilities to operate the chair in a variety of environments. Finally, it incorporates a mechanism for automatically selecting between these modes during operation (described in [25]).

III. HARDWARE

The NavChair prototype is based on a Lancer[3] power wheelchair. The components of the NavChair system are attached to the Lancer and receive power from the chair's batteries. As shown in Fig. 2, the NavChair system consists of three units: 1) a DOS-based, 33 MHz, 80486 computer, 2) an array of 12 ultrasonic transducers mounted on the front of a standard wheelchair lap tray, and 3) an interface module which provides the necessary circuits for the system.

The Lancer's controller is divided into two components: 1) the joystick module, which receives input from the user via the joystick and converts it to a signal representing desired direc-

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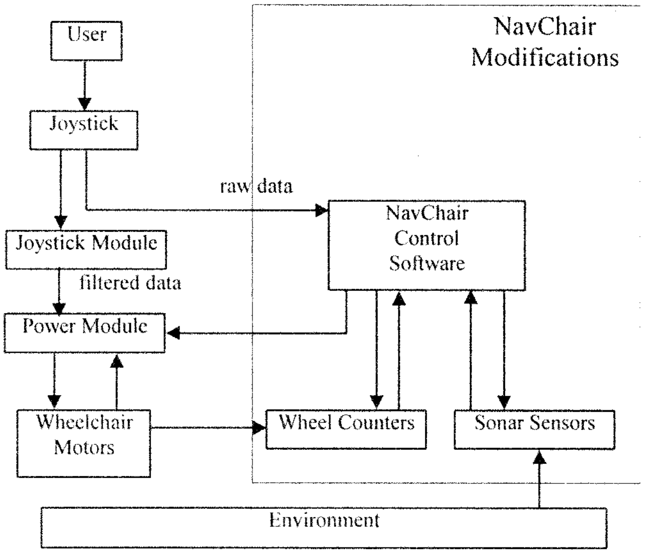
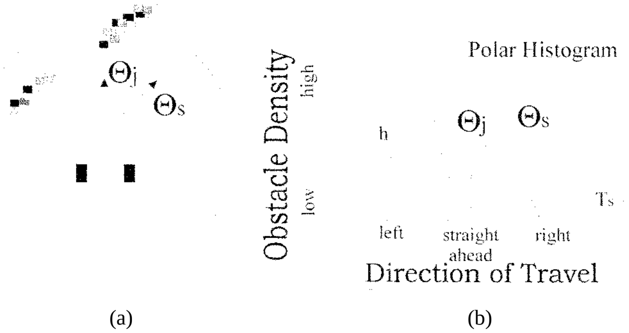


Fig. 2. Functional diagram of the NavChair prototype's hardware components [2].

tion and 2) the power module, which converts the output of the joystick module to a control signal for the left and right wheel motors. During operation, the NavChair system interrupts the connection between the joystick and the power module, with the joystick position (representing the user's desired trajectory) and the readings from the sonar sensors (reflecting the wheelchair's immediate environment) used to determine the control signals sent to the power module [16]. The NavChair's software performs the filtering and smoothing operations that were originally performed by the joystick module after the navigation assistance calculations have been performed.

Sonar sensors are used because of their operational simplicity and low cost. However, individual sonar readings are often erroneous. The 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 [8]. EERUF rejects bad sonar readings by detecting temporal patterns inconsistent with error-free operation. The accuracy of the map is further enhanced by keeping track of the wheelchair's motion via 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. The NavChair is able to accurately locate obstacles within five degrees of angular resolution relative to the center of the chair despite the fact that the resolution of an individual sonar sensor exceeds 15 degrees [3].



(a) (b)

Fig. 3. 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; $\mathbf{h}$ is the polar histogram representing obstacle densities in each possible direction of travel; $\mathbf{T_s}$ is the safety threshold value; Θ_s is the safe direction of travel selected by VFH.

IV. OBSTACLE AVOIDANCE METHODS

Two obstacle avoidance routines, minimum vector field histogram (MVFH) obstacle avoidance and vector force field (VFF) obstacle avoidance, are used by the NavChair. Both routines are based on methods originally developed for autonomous mobile robots that were modified to meet specific requirements for wheelchair navigation. The influence of each routine on the NavChair's direction of travel at any given time is determined by the NavChair's current operating mode and readings from the ultrasonic sensors reflecting the status of the immediate surroundings. An overview of these routines follows.

The obstacle avoidance technique first used in the NavChair, the vector field histogram method (VFH) [6], [7] was originally developed for autonomous mobile robots. The VFH algorithm is illustrated in Fig. 3 and can be described briefly as follows.

1) Input from the sonar sensors and wheel motion sensors is used to update a Cartesian map (referred to as the *certainty grid*) centered around the chair. The map is divided into small cells, each of which contains a count of the number of times a reading has placed an object within that cell. The count within each cell, the *certainty value*, represents the probability that an object is within that cell; so the more often an object is seen within a cell the higher its certainty value.
2) The certainty grid 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 distance between that object and the wheelchair) versus direction of travel [6], [7].
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.

After the VFH algorithm has been applied, the chosen direction and speed are further modified by the VFF algorithm. Like VFH, the VFF method was originally developed for cylindrical autonomous robots [5] and then enhanced to work with irregularly shaped mobile robots [9]. In essence, VFF works by allowing every object detected by the NavChair's sonar sensors to exert a repulsive force on the NavChair's direction of travel, modifying its path of travel to avoid collisions. The repulsive force exerted by each object is proportional to its distance from the vehicle. To account for the NavChair's rectangular shape, five different points on the chair are subject to the repulsive forces (Fig. 4). The repulsive forces at each of these five points is summed and this total repulsive force is used to modify the NavChair's direction of travel.

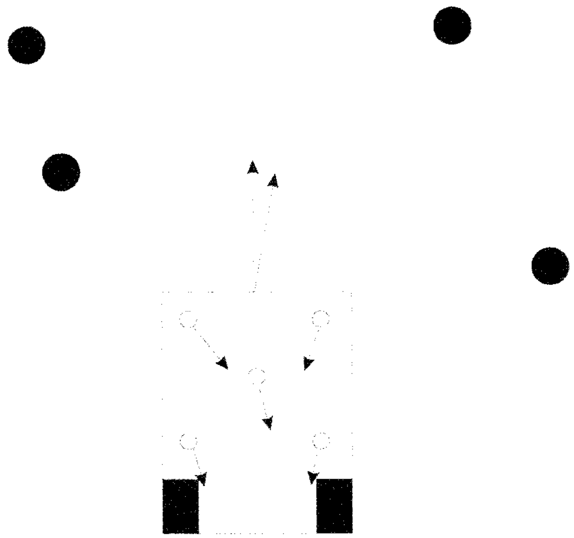
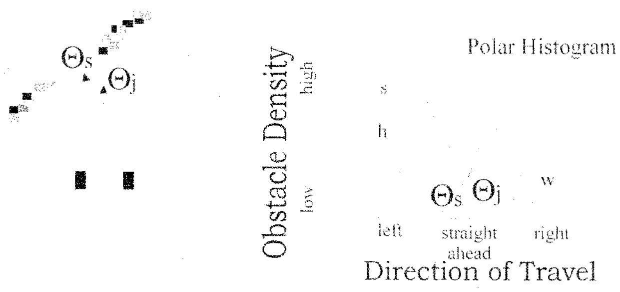


Fig. 4. Example of VFF Operating in The NavChair. The black circles represent obstacles, the gray circles are the five locations at which the repulsive forces are calculated, the lines extending from the gray circles represent the repulsive forces at each of these points (size of the arrows is proportional to magnitude of the repulsive force), the dashed line represents the direction the user pressed the joystick, and the solid line is the direction actually chosen by VFF.



(a) (b)

Fig. 5. 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_j); **s** is the sum of **h** and **w**; Θ_s is the actual direction of travel selected by MVFH at the minimum of **s**.

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. One difficulty in applying an obstacle avoidance routine developed for a robot to a wheelchair was the different types of movement employed by the two platforms. Mobile robots in general (and those VFH was originally intended for in particular) are cylindrical and omni-directional, which simplifies the calculation of trajectories for collision avoidance. However, when applied to a rectangular wheelchair with arced trajectories, failures of the obstacle avoidance routine are more likely. Another difficulty arose from the fact that VFH could not support all of the desired functions (door passage and close approach in particular) while still maintaining adequate obstacle avoidance protection in more open environments. Finally, what was considered one of the VFH method's greatest strengths in robot applications, the ability to move through a crowded environment and make abrupt changes in direction with a minimal reduction in speed, was unacceptable behavior for the wheelchair application where it was likely to be considered "jerky" and unpredictable.

In response to these needs, the Minimal VFH (MVFH) method was developed [1], [4]. The steps of the MVFH algorithm are illustrated in Fig. 5. The first two steps are identical to VFH. However, unlike the VFH method, the third step of the process does not simply search for the closest direction of travel to that desired with an obstacle density below the given threshold. Instead, a weighting function (curve **w** in Fig. 5) is summed with the polar histogram (curve **h**) to produce curve **s**. The direction of travel (Θ_s) is then chosen as the direction corresponding to the minimal value for curve **s**. The weighting function (**w**) 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*) while directions furthest from the user's goal receive the most weighting, predisposing the chair to pursue a direction close to the user's goal.

In the fourth step of the MVFH method the wheelchair's speed is determined based on the proximity of obstacles to the projected path of the chair. This step takes in to account the rectangular shape and nonholonomic nature of the wheelchair when calculating the projected path, which allows the chair to approach objects more closely than VFH while still maintaining the safety of the vehicle. Unlike in the VFH algorithm, the virtual force repulsion (VFF algorithm) is not automatically applied in the MVFH algorithm. Rather, it is active during the performance of some tasks, like traveling through a crowded room, where it helps to maintain adequate clearance from all obstacles, but not others like following a wall down a hallway, where it would otherwise interfere with the wheelchair's ability to remain close to the wall (see *The Navchair's Operating Modes* below).

A. Experimental Testing of MVFH

Five tests were run, which compared the performance of VFH, MVFH, and that of an experienced wheelchair operator using the unmodified wheelchair control system [1]. VFF was active in combination with both VFH and MVFH for all tests. The tests were performed in a U-shaped hallway with two right-angle turns, and contained difficult situations typical of modern office buildings: mixed smooth tile and rougher concrete walls, a section of glass wall, and narrow doorways. The test course was approximately 2 m wide and 30 m long. In all tests, four quantitative measures of performance were collected to be used as the basis of comparison: average speed (m/s), ride "wobble" (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 these variables.

TABLE I

MVFH VERSUS VFH IN THE HALLWAY ENVIRONMENT [10]. FOUR MEASURES OF PERFORMANCE (AVERAGED OVER FOUR TRIALS) ARE COMPARED FOR A BLINDFOLDED SUBJECT USING OBSTACLE AVOIDANCE AND AN EXPERIENCED SUBJECT USING THE UNMODIFIED WHEELCHAIR CONTROL SYSTEM IN THE SMOOTH HALLWAY COURSE. STANDARD DEVIATIONS FOR ALL MEASURES WERE LESS THAN 10% OF MEAN. THE RESULTS INDICATE THAT THE BLINDFOLDED USER IS ABLE TO TRAVEL SAFELY AT ABOUT HALF THE SPEED OF THE EXPERIENCED USER TRAVELING WITHOUT OBSTACLE AVOIDANCE. NOTE THAT OBSTACLE CLEARANCE WAS ONLY MEASURED DURING THOSE TRIALS IN WHICH THE USER WAS BLINDFOLDED AND ACTIVELY STEERING THE WHEELCHAIR TOWARDS THE WALL (TESTS 1 AND 3), AND THAT RIDE WOBBLE WAS ONLY RECORDED WHEN THE NAVCHAIR WAS PROVIDING NAVIGATION ASSISTANCE (TESTS 1–4)

Performance Measure	VFH		MVFH		Experienced User
	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
wobble	0.95	0.68	0.58	0.55	n/a
collisions	0	0	0	0	0

The first two tests evaluated VFH obstacle avoidance. In Test 1 the user was blindfolded and traversed the course by holding the joystick toward the wall, at approximately a 45° angle, while in Test 2 the user attempted to steer the chair straight down the middle of the hallway by pointing the joystick straight ahead. 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. Each test was repeated four times with a single user and the results averaged.

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

There were several advantages of MVFH not brought out by the experimental results which deserve mention. First, using MVFH, control of the chair became much more intuitive and responsive. Small changes of the joystick position resulted in changes in wheelchair motion, which was not always true under VFH control. Second, by modeling the exact shape of the NavChair it was possible to perform previously unmanageable tasks, such as passing through doorways. Most importantly, however, MVFH provided an adaptable level of navigation assistance. By changing the shape of the weighting function, MVFH could assume more or less control over travel decisions. This flexibility allowed the development of multiple task-specific operating modes for the NavChair.

V. THE NAVCHAIR'S OPERATING MODES

During the design of the NavChair system it became clear that in order to provide the full range of desired functionality it would be necessary to define several different operating modes [1], [2]. This section describes the function of each of the three operating modes currently implemented within the NavChair: General Obstacle Avoidance, Door Passage and Automatic Wall Following. The results of several experiments are also presented to provide performance data for each operating mode.

A. General Obstacle Avoidance Mode

General Obstacle Avoidance (GOA) mode is the "default" operating mode of the NavChair and is intended to allow the NavChair to quickly and smoothly navigate in crowded environments while maintaining a safe distance from obstacles. MVFH and VFF are both active in this mode. The weighting function used by MVFH is a relatively wide parabola (compared to the NavChair's other operating modes) centered on the joystick direction, which allows the chair a relatively large degree of control over its direction of travel. Of the three modes described in this paper, this mode allocates the most navigation control to the NavChair in that it has great freedom in choosing a direction of travel while attempting to remain close to the direction indicated by the user.

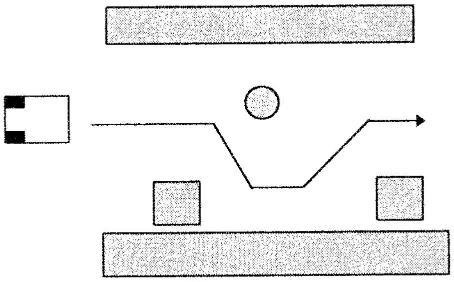


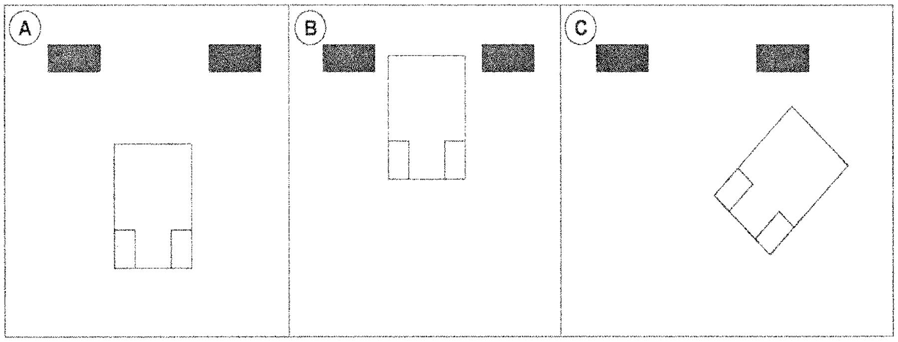
Fig. 6. The course for testing of general obstacle avoidance versus no navigation assistance.

A simple experiment was performed to analyze GOA mode's ability to successfully navigate the NavChair through a crowded room [23]. The experimental environment is shown in Fig. 6. A fully capable driver performed ten trials with the NavChair in GOA mode and ten trials with no navigation assistance active (in other words, the NavChair behaved exactly like a normal power wheelchair). In each trial the subject's task was to follow the path indicated in Fig. 6. Results from the ten trials were averaged.

The results of the experiment are shown in Table II. They reveal that GOA mode caused the NavChair to move more slowly through the slalom course than occurred when navigation assistance was not active. However, the NavChair also maintained a greater minimum distance from obstacles in GOA mode, due to the influence of the NavChair's collision avoidance routines.

B. Door Passage Mode

Door Passage (DP) mode is intended for use in situations requiring the NavChair to move between two closely spaced



(a) (b) (c)

Fig. 7. Panel A shows a situation that would where it is appropriate for the NavChair to enter DP mode. If the wheelchair operator directs the NavChair toward the door, DP mode will act to center the chair in the doorway and move the chair through the door (Panel B). However, if the wheelchair operator directs the chair away from the door, DP mode will not push the chair through the door (Panel C).

TABLE II
RESULTS FROM EXPERIMENT COMPARING GENERAL OBSTACLE AVOIDANCE MODE WITH NO NAVIGATION ASSISTANCE. STANDARD DEVIATIONS FOR ALL MEASURES WERE LESS THAN 6% OF MEAN

Performance Measure	General Obstacle Avoidance	No Navigation Assistance
Time (sec)	9.35	7.09
Average Speed (m/sec)	0.61	0.76
Average Minimum Obstacle Clearance (m)	0.59	0.53

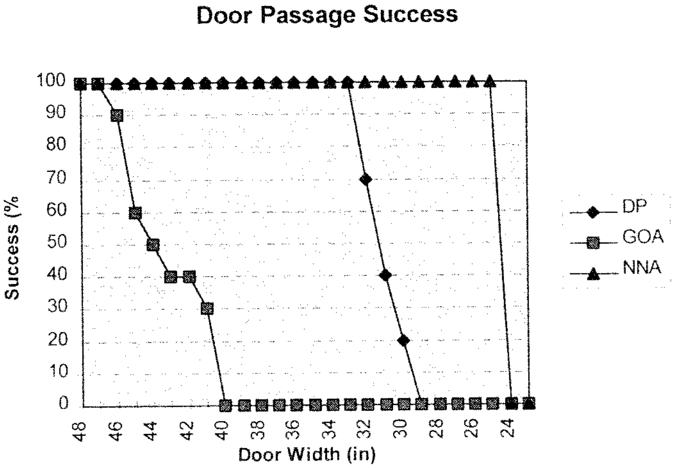


Fig. 8. Results from an experiment comparing the performance of door passage mode (DP), general obstacle avoidance mode (GOA), and no navigation assistance (NNA) on a door passage task.

obstacles, such as the posts of a doorway. DP mode acts to center the NavChair within a doorway and then steer the chair through it. In this mode, VFF is not active and MVFH's weighting function is a narrow parabola, forcing the NavChair to adhere closely to the user's chosen direction of travel.

Fig. 7 shows the operation of DP mode. As the chair passes through the doorway, MVFH acts to push the chair away from both door posts and toward the center of the door. MVFH also acts to reduce the chair's speed as it approaches the doorway. If the user points the joystick in the general direction of a door, the effect is to funnel the NavChair to the center and through an open doorway.

Due to the influence of obstacle avoidance, it is possible for the NavChair to fail to successfully pass through a doorway on a given attempt. Typically, this is due to the NavChair approaching the door at an angle rather than from directly in front of the door. When a failure occurs, the operator is then required to back up and approach the door again, hopefully from a better direction.

An experiment was performed to compare the ability of GOA mode and DP mode to pass between closely spaced obstacles [23]. In this experiment a fully capable driver attempted to steer the NavChair through a door whose width was varied. Twenty trials were performed at each width. In ten of the trials the NavChair was in GOA mode and in ten of the trials the NavChair was in DP mode. Results from the ten trials for each mode were averaged and are shown in Fig. 8.

As can be seen from the graph, DP mode allowed the NavChair to pass through significantly smaller spaces than GOA. Of particular interest, the NavChair successfully passed through spaces 32 inches (81.3 cm) wide 70% of the time. This is noteworthy because the federal Architectural and Transportation Barriers Compliance Board [27] has declared 32 inches as the minimally acceptable door width for wheelchair accessibility in federal buildings. With no navigation assistance active, the NavChair was able to pass through doorways as small as 25 inches (63.5 cm), which corresponded to the width of the NavChair.

C. Automatic Wall Following Mode

Automatic Wall Following (AWF) mode causes the NavChair to modify the user's joystick commands to follow the direction of a wall to the left or right of the chair. In this mode neither MVFH nor VFF is active. Instead, the NavChair uses the sonar sensors to the front and side of the opposite the wall being followed to scan for obstacles while the remaining sonar sensors (facing the wall) are used to navigate the chair. The NavChair's speed is reduced in proportion to the distance of the closest detected obstacle, which allows the NavChair to stop before a collision occurs.

Fig. 9 shows the operation of AWF mode. As long as the user points the joystick in the approximate direction of the wall being followed, the chair modifies the direction of travel

TABLE III

RESULTS OF AN EXPERIMENT COMPARING THE PERFORMANCE OF AUTOMATIC WALL FOLLOWING MODE, GENERAL OBSTACLE AVOIDANCE MODE, AND NO NAVIGATION ASSISTANCE ON A HALLWAY TRAVERSAL TASK. STANDARD DEVIATIONS FOR ALL MEASURES WERE LESS THAN 6% OF MEAN

Performance Measure	Automatic Wall Following	General Obstacle Avoidance	No Navigation Assistance
Average Time (sec)	9.13	11.27	4.60
Average Speed (m/sec)	0.76	0.63	1.45
Average Minimum Clearance (m)	0.41	0.56	0.32

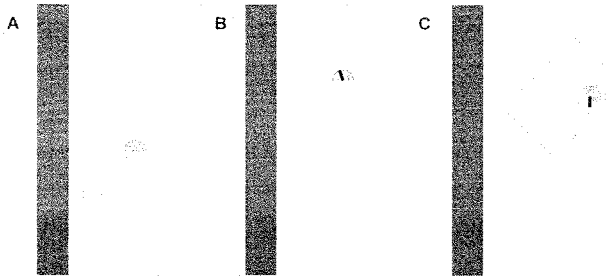


Fig. 9. Panel A shows a situation where it is appropriate for the NavChair to use AWF mode. The circle represents potential joystick inputs. If the user continues to direct the chair along a path roughly parallel to the wall (i.e., joystick position anywhere in the shaded portion of the circle) the NavChair will follow the direction of the wall (Panel B). However, if the user directs the chair in a direction sufficiently different from the wall (i.e., anywhere outside the shaded portion of the circle) the NavChair will leave AWF mode and move away from the wall (Panel C). The sonar sensors facing the wall are used to follow the wall while the sonar sensors in front of the chair are used to scan for obstacles.

to follow the wall while maintaining a safe distance from the wall. However, if the user points the joystick in a direction sufficiently different from that of the wall then the user's direction is followed instead.

An experiment was performed to compare the performance of the NavChair operating in GOA mode, in AWF mode, and without navigation assistance in a hallway traversal task [23]. In this experiment a fully capable driver performed thirty trials in which he attempted to navigate the NavChair down an empty hallway. In ten of the trials the NavChair was in GOA mode and the subject moved the NavChair down the hallway by pointing the joystick at a 45° angle to the wall. In the second set of ten trials the NavChair was in AWF mode. In the final set of ten trials, the NavChair's navigation assistance was not active. Results from each set of ten trials were averaged.

The results of the experiment appear in Table III. They show that AWF mode allowed the NavChair to travel at a faster speed closer to a wall then GOA mode; but did not allow the chair to travel as fast or as close to the wall as was possible for an able-bodied operator using the chair without navigation assistance. However, AWF is expected to provide a measurable improvement in performance for the NavChair's target user population, defined by their inability to operate a power wheelchair, as well as able-bodied individuals.

VI. DISCUSSION

While the NavChair has yet to be formally evaluated in trials with potential users, feedback has been sought from clinicians active in wheelchair seating and mobility during all phases of the its design and development. Additionally, informal sessions with potential users have provided encouraging results. Formal user trials are planned for the very near future.

The NavChair has demonstrated satisfactory performance in all operating modes using a standard joystick controller. This provides a good indication of the NavChair's ability to deliver the navigation assistance needed by individuals who can not operate or have difficulty operating a standard power wheelchair. However, as should be expected, the NavChair's level of performance is not equal to that of a competent user.

The primary reason that navigation assistance does not match skilled driving performance is the tendency for it to reduce the wheelchair's speed. Another problem arises from the lack of resolution provided by the NavChair's sonar sensors. A skilled wheelchair operator, guided by visual feedback, can steer much closer to obstacles without fear of collision than is possible for the NavChair's software guided by sonar sensors. This results in the NavChair maintaining a greater minimum distance from obstacles than is strictly necessary.

Beyond its application for people who have difficulty operating a powered wheelchair, the NavChair has been used as a test-bed for research in automatic adaptation of human–machine systems [1], [2], [23]. The presence of multiple operating modes necessarily creates the need to choose between them. One alternative is to make the wheelchair operator responsible for selecting the appropriate operating mode. While this may be an effective solution for some users, it would place unreasonable demands on others. Instead, the NavChair has been used to evaluate different methods for allowing it to automatically select the correct operating mode based on user behavior and environmental status [23], [25].

The NavChair also has potential as an attractive test-bed for exploring alternative wheelchair interfaces. It can be used to examine the performance of different input (e.g., voice) and feedback (e.g., auditory and visual) options that are currently unavailable on standard power wheelchairs. It also can be used in conjunction with alternative input methods such as voice control in order to enhance system performance.

Future development work is planned in several areas. First, the need for formal testing of the NavChair with potential users will require that the NavChair be modified to accommodate the multitude of seating and positioning hardware that these users normally employ. In addition, the NavChair will also have to accommodate a larger variety of input methods, such as head joysticks, pneumatic controllers, and switch arrays.

There is also a need to add more environmental sensors to the NavChair. Currently, the NavChair has very few sensors on its sides and does not have any sensors at all in back. This can cause the NavChair to become confused when moving within a tightly confined area. In addition to sonar sensors, infrared range finders and bump sensors should be added to the NavChair to improve the capability of its obstacle avoidance routines.

Another area for development is the addition of operating modes for the NavChair. A close approach mode is envisioned which will allow a user to "dock" the NavChair at a desk or table. Modes for more autonomous operation with discrete control methods such as switches and voice are also needed [24]. For those with the most severe disabilities there is also a need for a fully autonomous mode. This mode has already been successfully demonstrated informally within the laboratory setting and is based on a global environmental map and a path planning routine available from the autonomous mobile robot work which led to the NavChair.

VII. CONCLUSION

Advances have been made in the technology of "smart wheelchairs" during the development of the NavChair. Performance of the NavChair has demonstrated its potential as an effective approach to providing independent mobility to a wide range of users who can not independently operate a powered wheelchair system. The design of the NavChair readily allows for different operating levels ranging from simple obstacle avoidance to fully autonomous navigation. Additionally, the NavChair provides a means for development and testing of "shared control" methods, where a human operator and machine share control of a system. Results from research and development efforts in this area should have application to a broad range of assistive technology systems.

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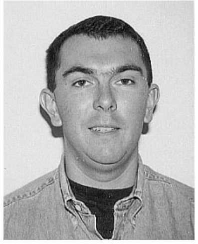

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