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An Assistive Navigation System for Wheelchairs Based upon Mobile Robot Obstacle Avoidance

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Abstract

The NavChair assistive navigation system is being developed to meet the needs of multiply handicapped people who are unable to operate available wheelchair systems. The NavChair Project was conceived as an application of mobile robot obstacle avoidance to a power wheelchair. During the course of this project, the Vector Field Histogram (VFH) method has been adapted for use in human-machine systems and the shortcomings of the wheelchair platform have been overcome. This paper briefly reviews the VFH method, describes interesting aspects of its application to a power wheelchair, and presents an experimental evaluation of system performance. Finally, unresolved problems of obstacle avoidance in human-operated vehicles are discussed.

Introduction

The NavChair assistive navigation system [1, 2] is being designed to improve the mobility and safety of people who have sensory, perceptual or motor impairments that limit their ability to operate a power wheelchair. For example, tremor, paralysis, and visual impairment prevent many people from effectively operating existing wheelchair systems. The NavChair control system is being built to avoid obstacles, follow walls, and travel safely in cluttered environments under the direction of the wheelchair user. This paper outlines research into the application of robotic obstacle avoidance to this power wheelchair assistive navigation system.

The NavChair is a human-machine system in which the machine must share control with the user [3]. Obstacle avoidance should modify the user's input command to achieve safe travel.. This approach gives the user high-level control of wheelchair motion while overriding unsafe maneuvers. Vector Field Histogram (VFH) obstacle avoidance [4, 5] was selected for this project because it is familiar to the authors and because it has provided effective sonar-based obstacle avoidance for mobile robots [6].

Two types of problems were encountered in the application of the VFH method to a power wheelchair system. First, the power base is significantly different than typical mobile robots. For example, the pneumatic tires, wheel slippage, and loose drive train make wheelchair dead-reckoning accuracy an order of magnitude worse than in most mobile robots. A second type of difficulty is related to the application of obstacle avoidance to a human-machine system. Safe travel is only one of several requirements for the NavChair controller. The user must also feel safe and in control of the wheelchair; the system's reaction to input must be intuitive enough to inspire confidence and smooth enough for comfortable travel. The VFH method was originally developed for autonomous mobile robots under a significantly different set of performance goals.

The next section outlines the VFH obstacle avoidance method. Some of the difficulties encountered in applying obstacle avoidance to the NavChair are discussed, along with available solutions. Quantitative measures of system performance are presented and used to compare system performance for a blindfolded person using obstacle avoidance and an experienced user.

Methods

Obstacle avoidance

The basic operation of the VFH method is outlined in figure 2. The method consists of four stages:

1. Sonar readings are accumulated in a two-dimensional grid that represents the probable locations of obstacles around the wheelchair;
2. Obstacle data is reduced into a one-dimensional polar histogram, which indicates time to collision versus direction of travel;
3. This histogram is searched for the collision-free direction closest to the target direction specified by the user via the joystick
4. The free direction and the wheelchair speed are modified by an amount proportional to a virtual obstacle repulsive force.

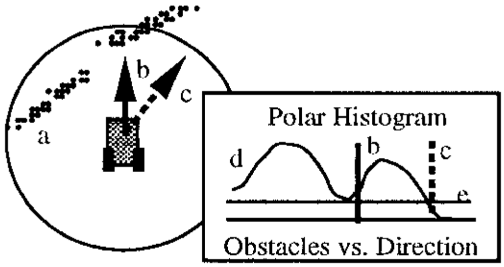

Figure 1: Vector Field Histogram Obstacle Avoidance: Sensor readings are used to update a map of obstacles in the form of a *certainty grid (a)* in which obstacles are represented as areas of high obstacle certainty. The certainty grid is used to calculate a *polar histogram (d)* in which high values represent close and/or large obstacles. The *target direction* specified by the user via the joystick (solid arrow, b) is modified to a *free direction* (dotted arrow, c). VFH finds the direction closest to the target direction that is below a *safety threshold (e)*. This method allows the NavChair to steer automatically around obstacles while giving the user high-level control of wheelchair motion.

Sonar sensors were selected for this project because they have been shown to work effectively with VFH and because their low cost improves the chance that the results of this research can be applied directly to commercial wheelchairs. One drawback of sonar sensors is that rapid firing causes interference between nearby sensors (crosstalk) [7]. However, slow firing limits the maximum safe speed of the wheelchair [8]. A method called Error Eliminating Rapid Ultrasonic Firing (EERUF) [9] has been developed at the University of Michigan that allows rapid sonar firing by detecting and discarding readings caused by interference. EERUF works well in conjunction with the VFH method, because both systems accumulate data in a way that decreases system sensitivity to false readings. EERUF rejects bad readings by detecting temporal patterns inconsistent with the firing pattern. The VFH method accumulates data from the entire sonar array in a certainty grid that requires repeated readings in the same location.

EERUF and the VFH data accumulation take advantage of an important source of information about the sonar readings: the motion of the wheelchair. The result is that the NavChair can use an array of moving sonar sensors to create accurate 2-D maps of nearby obstacles despite the fact that sonar readings individually contain limited information. The angular resolution of the certainty grid data, for example, is better than 5 degrees relative to the center of the chair even though the resolution of individual sensors is worse than 15 degrees. Using VFH with EERUF, the chair is not stopped by crosstalk images and real obstacles are seen rapidly enough for effective reaction.

Applying VFH to a Power Wheelchair

The NavChair system consists of a commercial power wheelchair equipped with a 486-based portable computer and Polaroid [10] ultrasonic range detectors. The computer runs VFH obstacle avoidance software in a 30 millisecond loop with display and sonar functions handled in the background. Each time through the loop, the computer reads the joystick command, updates the histogram with new sonar readings, performs obstacle avoidance calculations, and sends a modified command to the drive motors. Detailed descriptions of hardware and low-level software are available elsewhere [11].

Power wheelchairs have very poor dead reckoning abilities. Dead reckoning is necessary for effective spatial data accumulation. Even in straight travel, variations in wheel diameter due to load shifts cause angular accuracy to be an order of magnitude worse than in most mobile robots. Angular errors are especially harmful for dead-reckoning because they can cause unbounded growth of lateral position errors. Turns, variable surface characteristics, and wheel slippage make this problem even worse.

Dead reckoning errors were measured and minimized during the course of this project. However, we found that poor dead-reckoning was unavoidable without a complete redesign of the wheelchair. However, the NavChair uses sonar readings effectively by refreshing the obstacle map rapidly enough to reduce the influence of old readings. We have found that dead reckoning errors are not an important impediment to effective obstacle avoidance.

The complex geometry and kinematics of the NavChair are substantially different than those of most robotic systems. The NavChair has a rectangular footprint and cannot rotate about its center, which make the computation of obstacle distance and free-paths difficult. Most obstacle-avoidance systems use a round model of the robot to insure that collisions do not occur. This method produces collision-free travel, but can be too conservative for non-round robots. If the NavChair is modeled as a disk, it needs a free space around its center of rotation 2 meters in diameter to insure safe travel. Even the smallest circle enclosing the NavChair has a diameter of about 1.5 meters. These approaches often prevent door passage and leave little margin of safety at the front of the chair. This problem has been addressed by applying a "non-point VFH" method [12] to the NavChair which involves the use of multiple potential force points to protect the outline of the chair. This method allows the safe area around the chair to be substantially smaller than a circle.

The presence of human users in the control loop places additional constraints on the behavior of the wheelchair beyond those encountered with autonomous systems. First, human users have special smoothness and comfort requirements. Simple smoothing is not sufficient for this purpose because issues of biomechanical feedback, obstacle avoidance performance degradation due to delay, and safety severely limit the types of filters that can be used. The final system consisted of a ten-step filtering procedure that includes a delay, data processing routines, low-pass filters, acceleration limits, and velocity limits. This process provides acceptably comfortable travel and effective obstacle avoidance.

The control of human-machine systems must be intuitive for the user. Unintuitive control increases training time and reduces the ability of the user to adapt to unusual circumstances. "Intuitive" control means, among other things, that the user must feel that the wheelchair's responses to input are rational and predictable. One of the great strengths of the VFH method with autonomous and semi-autonomous mobile robots is actually a drawback when the user is onboard. VFH allows relatively fast travel through cluttered environments by avoiding obstacles with only a minimal reduction in speed. However, when the user is onboard, this behavior is perceived as a sudden and unpredictable change in direction.

We modified the VFH method to slow the chair by an amount proportional to the difference between the command direction and the direction of travel selected by obstacle avoidance. In this way, the user "feels" the presence of the obstacle through the speed reduction as the wheelchair begins to turn. This method limits the range of possible commands: directions that are too far from the direction specified by the user slow the chair to a halt. In an autonomous system, this would result in the robot "getting stuck;" in a human-machine system, it informs the user that the current path is blocked and that another path must be attempted.

Experimental Results

System performance is a function of quantitative measures as well as subjective ratings of comfort and safety. These measures include:

- average speed -- m/sec.
- jerkiness -- RMS average of the portion of the obstacle avoidance motor command above 10 Hz.
- average obstacle clearance -- The average distance from the side of the wheelchair to the nearest obstacle.
- collision risk -- collisions and near misses per s.

During the course of the NavChair project, numerical measures of system performance have been used to chart progress and quantify improvements. System performance is determined primarily by eight important obstacle avoidance parameters. The results presented here refer to the parameter set that produces the best system performance as measured by the variables above.

Three tests were performed in a smooth hallway environment illustrated in figure 3. Many types of difficult trap situations are present in this course. The walls are smoothly painted drywall uninterrupted by marks, cracks or other features that the sonar might detect. As the result, the wall is visible to the system only directly to the side of the NavChair where the echo is reflected straight back at the sensors. In *test 1*, a blindfolded user points the joystick into the walls (at 45°) and follows each wall once in each direction using obstacle avoidance. In *test 2*, a blindfolded user points the joystick straight ahead and allows the NavChair to travel down the middle of the hall and turn corners (if possible) on its own. In both of these tests, the user moves the joystick slightly to keep the NavChair moving if it gets stuck, such as when the joystick is pointing into a corner. In *test 3*, an experienced user covers the course as rapidly as possible without obstacle avoidance.

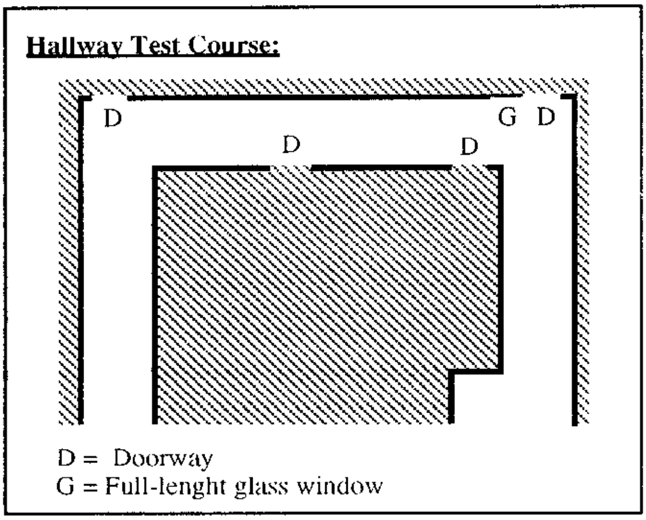

Figure 2: Smooth Hallway Test Course: Testing was performed in an unmodified hallway at the University of Michigan typical of the hallways found in modern buildings. This particular hallway includes difficult trap conditions: smooth halls occasionally interrupted by easily-seen obstacles; a segment of glass wall; and doors barely narrow enough for passage. The course is approximately 30 m in length and 2 m wide.

Hallway Test:	test 1	test 2	test 3
Average speed	0.73 m/s	0.78 m/s	1.62 m/s
Wall distance	0.436 m	n/a	n/a
Jerkiness	94.7	68.3	203.2
Collisions	0	0	0

Table 1: Obstacle Avoidance in 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 expert user is able to travel about twice as fast as the blindfolded user and that neither experience collisions.

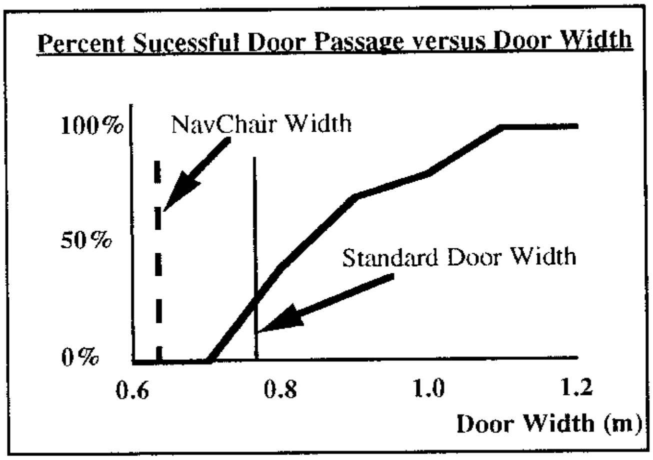

Figure 3: Door Passage Test Results: Percentage of successful door passage versus door width. Two marks provide scale: 1) dashed line: the NavChair is 0.63 m wide; and 2) solid line: standard doors (i.e. those that meet most building code regulations) are 0.76 m wide. Standard doors are just slightly wider than the NavChair.

Table 1 compares the results of these tests. The experienced user is able to travel about twice as fast as the blindfolded user with obstacle avoidance. However, the obstacle avoidance provides much smoother travel. No collisions occurred in any of the tests. The experienced user is included as an indication of optimum wheelchair performance. Thus the NavChair system allows a blindfolded person to operate the wheelchair safely and smoothly at reasonable speeds (50% of experienced user). The implication of these result is that the NavChair has good potential to provide functional mobility to people with multiple handicaps.

Another series of experiments investigated the ability of the VFH method to provide safe door-passage. The graph in figure 4 shows the percentage of successful door passages as a function of door width. As the width of the door decreases, the number of "balks" rapidly rises and the success rate drops to zero. The graph shows that standard doors can be successfully navigated only about 20% of the time. Passing through standard doorways is difficult for VFH obstacle avoidance because they are only 0.13 m wider than the NavChair. We conclude that the NavChair is not able to provide effective door-passage at this time.

One of the main thrusts of research in the NavChair project is to develop an effective door-passage controller. We feel that this goal is achievable. However, any control mode that allows safe passage through doors is likely to be substantially different than the controller for travel in a hallway. The availability of a door-passage controller separate from the main obstacle avoidance routine will make some method of mode selection necessary.

Discussion

Like many human-machine systems, the NavChair takes advantage of the capabilities of both the user and the machine by allowing them to share control of system output [13]. An important characteristic of human users is that they are able to adapt their control behavior to changes in environmental conditions and functional requirements. By allowing users to share control of the system, their adaptability improves the versatility and robustness of the entire system.

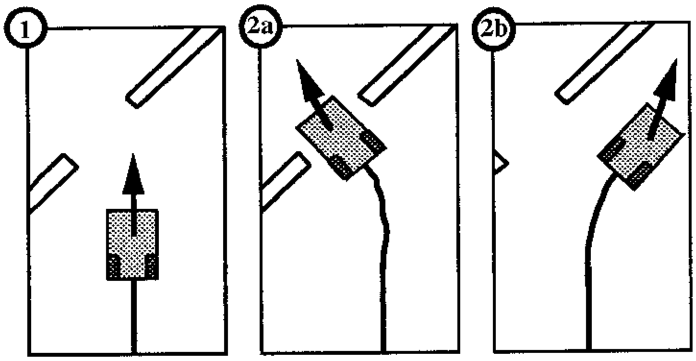

Figure 4: Mode Selection: The NavChair must be able to perform mode selection in the absence of environmental cues. Frame (1) shows the NavChair approaching a doorway in a flat wall. One of two outcomes is possible: either (2a) the NavChair performs door-passage behavior, or (2b) the NavChair performs an avoidance maneuver and continues to move forward in obstacle avoidance mode. These two behaviors correspond to two different modes of operation, door-passage and obstacle avoidance, that cannot be performed simultaneously.

Machine adaptation involves control system changes in response to estimates of system state and user behavior patterns. In many cases, environmental inputs do not uniquely determine how the control system should adapt, so this decision must be based upon an evaluation of user behavior [12]. A difficult issue we face in the design of an intelligent control system for the NavChair is to develop an effective way of adapting the behavior of the control system to the instantaneous needs of the user. In particular, an ability to perform autonomous mode selection seems necessary for the effective integration of door-passage and obstacle avoidance modes.

Figure 5 illustrates a mode selection problem. Any control system that effectively avoids collisions and allows smooth, uninterrupted travel in cluttered environments will not allow a user to move close to objects, such as the frame of a doorway. However, an ability to pass through normal doorways is very desirable. This situation is common: it is possible to design controllers to perform many important tasks, but it is not always possible to design one controller to perform all tasks. The result is that human-machine systems often need separate modes of operation that must be selectively activated. In a great many cases, this decision must be based upon user input. One solution, of course, is to have the user explicitly command the system to change mode. However, this approach only works if the person has the ability, knowledge, means, and opportunity to instruct the computer. In many cases, a more desirable solution would be for the system to make mode selections based upon observations of user behavior, freeing the user from conscious attention to the business of mode selection. This is an area of active research related to the NavChair project.

Conclusion

The NavChair project has been largely successful in applying VFH obstacle avoidance method, which was originally developed for mobile robots, to a power wheelchair. Many difficulties related to obstacle avoidance in a shared control system and the application of robotic techniques to a non-robotic system have been overcome. The resulting system is safe in a wide variety of indoor environments at relatively high average speeds. Tests show that the system allows a blindfolded person to travel safely at about half the speed of an experienced user. In other words, it has succeeded in providing basic mobility to someone who would otherwise need to be moved by an attendant.

However, there are important unresolved problems that remain. As mentioned above, the wheelchair is not consistently able to pass through doorways of standard width. In addition, the sonar array of the NavChair detects obstacles only at about the height of the chair. It cannot, therefore, detect obstacles too low or high to be seen by the ultrasonic sensors, nor can it detect drop-offs.

Current research related to the NavChair Project focuses on these issues. In particular, we hope to produce controllers that can provide consistently safe door passage. In addition, we are actively researching ways of performing autonomous mode selection to allow a seamless integration of separate modes of operation; and we are attempting to apply some of the lessons we have learned in the NavChair project back to autonomous and teleautonomous mobile robots.

Acknowledgments

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