NavChair: An Assistive Wheelchair Navigation System with Automatic Adaptation

Richard C. Simpson[1], Simon P. Levine[2], David A. Bell[3], Lincoln A. Jaros[4],
Yoram Koren[5], and Johann Borenstein[5]

[1] Metrica Corporation
1012 Hercules, Houston
TX 77058
U.S.A.
[2] Rehabilitation Engineering Program
Depts. of Physical Medicine and Rehabilitation and Biomedical Engineering
University of Michigan, Ann Arbor, MI 48109
U.S.A.
[3] Amerigon Corporation
5462 Irwindale Avenue, Irwindale, CA 91706
U.S.A.
[4] PhaseMedix Consulting
24380 Orchard Lake Road, Suite 114
Farmington Hills, MI 48336
U.S.A.
[5] Department of Mechanical Engineering
University of Michigan, Ann Arbor, MI 48109
U.S.A.

1 Introduction

The NavChair Assistive Wheelchair Navigation System [1], shown in Figure 1, 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. The NavChair shares vehicle control decisions with the wheelchair operator regarding obstacle avoidance, door passage, maintenance of a straight path, and other aspects of wheechair navigation, to reduce the motor and cognitive requirements for operating a power wheelchair.

This chapter provides an overview of the entire NavChair system. First, the NavChair's hardware and low-level software are described, followed by a description of the navigation assistance algorithms which are employed. Next, three distinct modes of operation based on these navigation algorithms and implimented in the NavChair are presented. Finally, a method for mode selection and automatic adaptation is described.

2 System Overview

The NavChair prototype is based on a Lancer power wheelchair. The components of the NavChair system are attached to the Lancer and receive power from the

V. O. Mittal et al. (Eds.): Assistive Technology and AI, LNAI 1458, pp. 235–255, 1998.

chair's batteries. As shown in Figure 2, the NavChair system consists of three units: (1) an IBM-compatible 33MHz 80486-based 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.

Fig. 1. The NavChair Assistive Wheelchair Navigation 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 direction, 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 module and the power module, with the user's desired trajectory (represented by input from the joystick or an alternative user interface) and the the wheelchair's immediate environment (determined by readings from the sonar sensors) used to determine the control signals sent to the power module [2]. 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.

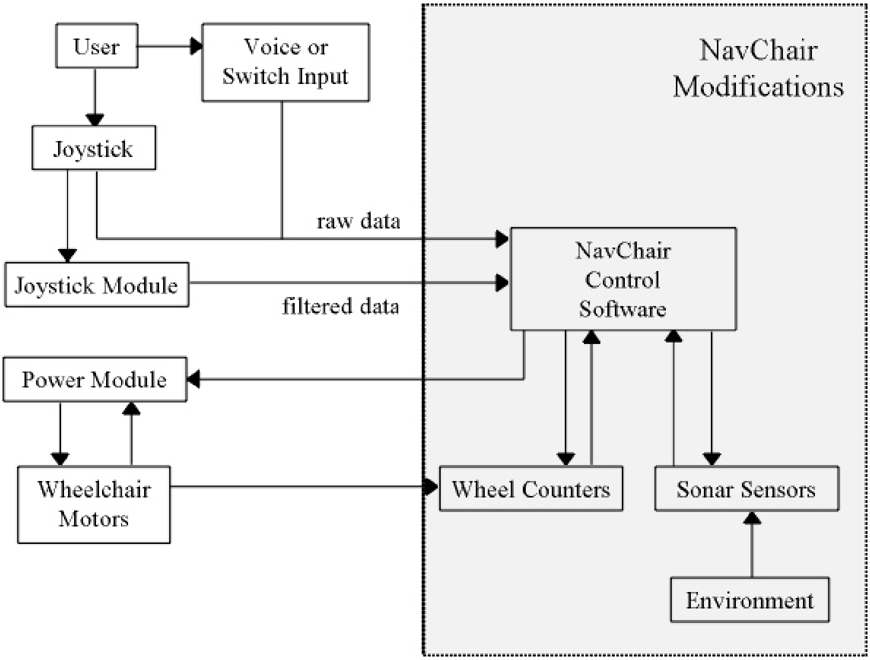

Fig. 2. Functional Diagram of The NavChair Prototype's Hardware Components [2]

In addition to the standard joystick control the NavChair has facilities for voice control. The voice control option is based on the Verbex SpeechCommander, a commercially-available continuous-speech voice recognition system that relays user commands to the NavChair via the computer's serial port. Prior to operation, users train the SpeechCommander to identify a small set of commands, a process which is typically accomplished in less than ten 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 pre- trained 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. The methods used for voice control also permit the use of discrete switches for Navchair operation.

Table 1 contains a list of the voice commands currently implemented within the NavChair. The NavChair's navigation assistance limits the commands needed to successfully complete most navigation tasks. Limiting the number of commands is desirable because it decreases the amount of time necessary to train the speech recognition system to recognize each subjects voice and the amount of time needed to teach each subject the voice control commands.

Table 1. 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.

The NavChair uses sonar sensors 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 [3]. 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 [4].

3 Navigation Assistance Algorithms

Two navigation assistance routines, Minimum Vector Field Histogram (MVFH and Vector Force Field (VFF), are used by the NavChair. Both stem from routines originally developed for obstacle avoidance in autonomous mobile robots. 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 immediate surroundings. This section describes the rationale behind both navigation assistance routines and gives an overview of each routine's operation.

3.1 Minimum Vector Field Histogram (MVFH)

The original obstacle avoidance technique used in the NavChair, the Vector Field Histogram method (VFH) [5,4], was originally developed for autonomous mobile robots. 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 is the different shapes of the two platforms. Mobile robots in general (and those VFH was originally intended for in particular) are round and omni-directional, 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 [6] it was determined that VFH could not support all of the desired functions (door passage in particular) while also ensuring the safety of the operator and vehicle during operation.

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.

In response to these needs, the Minimal VFH (MVFH) method was developed [7,8]. The MVFH algorithm proceeds in four steps:

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 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 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 different directions of travel.
3. A weighting function (curve w in Figure 3) is added to the polar histogram (curve h), and the direction of travel with the resulting minimal weighted

obstacle density (s) is chosen. As seen in Figure 3, 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.

4. The wheelchair's speed is determined based on the proximity of obstacles to the projected path of the chair. This step models the rectangular shape of the wheelchair exactly when calculating the projected path, which allows the chair to approach objects closely while still maintaining the safety of the vehicle.

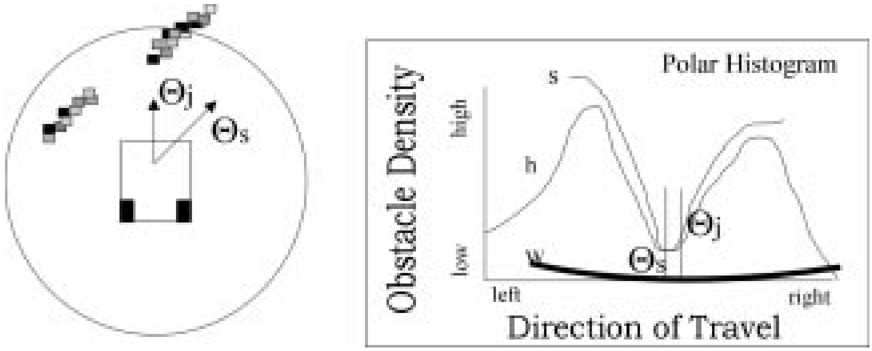

Fig. 3. MVFH Obstacle Avoidance. The left figure shows the certainty grid around the NavChair with darker shading of a cell corresdponing to a higher certainty value of an obstacle being at that location. The right figure shows the polar histogram at the same instant, where: j is the desired direction 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 (j); s is the sum of h and w; s is the actual direction of travel selected by MVFH at the minimum of s [9].

Using MVFH, control of the chair becomes much more intuitive and responsive. Small changes in the joystick's position result in corresponding changes in the wheelchair's direction and speed of travel. 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 allowed the development of multiple task-specific operating modes for the NavChair.

3.2 Vector Force Field (VFF)

A second obstacle avoidance routine intended for use in combination with MVFH is the Vector Force Field (VFF) method [9]. Like VFH, VFF was originally developed for round autonomous robots. The VFF method has been enhanced to work with irregularly shaped mobile robots [6] and has been applied to the NavChair system, as well (see Figure 4). In escence, 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. 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.

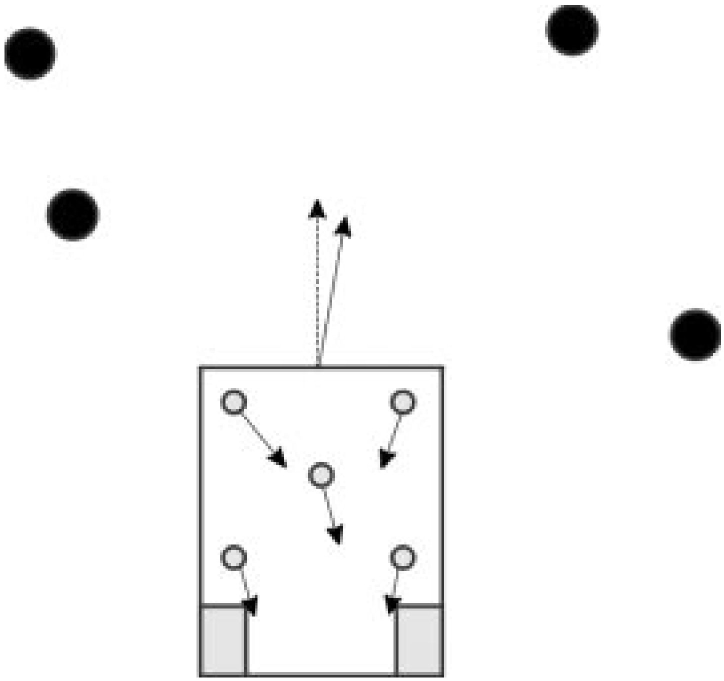

Fig. 4. Example of VFF Operating in The NavChair. The black circles represent obstacles, the gray circles are the five locations at which the repulsive forces are calculated, the lines extending from the gray circles represent the repulsive forces at each of these points (size of the arrows is proportional 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.

4 Operating Modes

During the design of the NavChair system it became clear that in order to provide the desired range of functionality it would be necessary to define several different operating modes [10]. This section describes the function of each of the operating modes currently implemented within the NavChair. The results of several experiments are also presented to provide insight into the nature of each operating mode.

4.1 General Obstacle Avoidance (GOA) Mode

General Obstacle Avoidance (GOA) mode is the "default" operating mode of the NavChair. GOA mode 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 the chair's direction of travel. This mode allocates the most control to the NavChair, in that it has great freedom in choosing a direction of travel to avoid obstacles while attempting to remain close to the direction indicated by the user.

A simple experiment was performed to analyze GOA mode's ability to successfully navigate the NavChair through a crowded room [11]. The experimental environment is shown in Figure 5. An able- bodied subject 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 Figure 5. The results of the experiment are shown in Table 2.

Table 2. Results from Experiment Comparing General Obstacle Avoidance Mode with No Navigation Assistance

Measure	General Obstacle Avoidance	No Navigation Assistance
Average Time (sec)	9.35	7.09
Average Speed (mm/sec)	606.19	758.72
Average Minimum Obstacle Clearance (mm)	591.74	526.06

As can be seen from Table 2, GOA mode caused the NavChair to move more slowly through the slalom course than was possible 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. It is important to note that the NavChair assistive navigation system is designed to assist people who might not otherwise be able to operate a power wheelchair. Thus, while it may slow the wheelchair down for a "best case" able-bodied user, it can also provide a level of performance not otherwise achievable for users whose impairments limit their ability to operate a powered wheelchair.

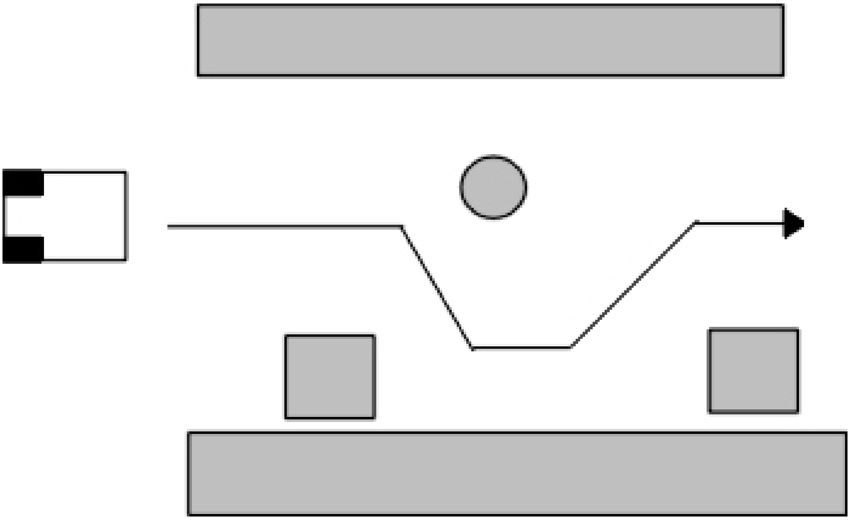

Fig. 5. General Obstacle Avoidance vs. No Navigation Assistance

4.2 Door Passage (DP) Mode

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

Figure 6 shows the operation of DP mode. As the chair passes through the doorway, MVFH acts to push the chair away from both doorposts and towards 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 forced to back up and approach the door again, hopefully from a better direction.

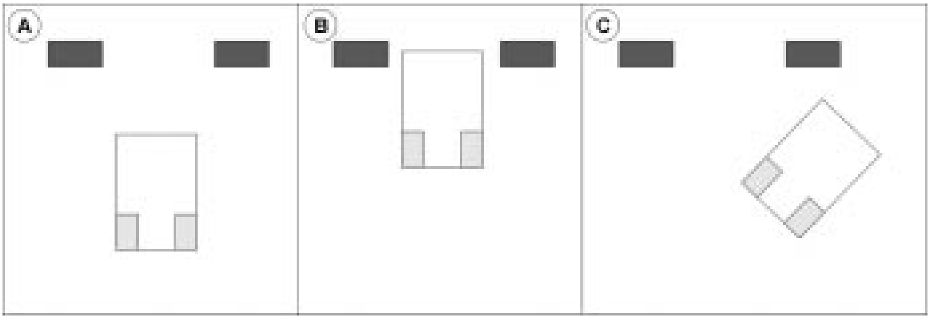

Fig. 6. Door Passage Mode. Panel A shows a situation that would prompt the NavChair to enter ADP mode. If the wheelchair operator directs the NavChair towards the door, ADP mode will act to center the chair in the doorway and move the chair through the door (Panel B). However, if the wheelchair operator directs the chair away from the door, ADP mode will not push the chair through the door (Panel C).

An experiment was performed to compare the ability of GOA mode and DP mode to pass between closely spaced obstacles [11]. In this experiment an able-bodied subject 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. The results of the experiment are shown in Figure 7.

As can be seen from the graph, DP mode allows 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 (1984) has declared 32 inches as the minimally acceptable door width for wheelchair accessibility in federal buildings. With no navigation assistance active, the NavChair is able to pass through doorways as small as 25 inches (63.5 cm), which corresponds to the width of the NavChair. This corresponds with the "best case" scenario in which navigation assistance is neither needed by the user nor provided by the NavChair. Once again, the NavChair's navigation assistance ability does not (nor is it expected to) match the performance of an able-bodied user, but does provide sufficient navigation assistance to allow users with difficulty operating a standard power wheelchair to successfully perform tasks such as passing through doorways.

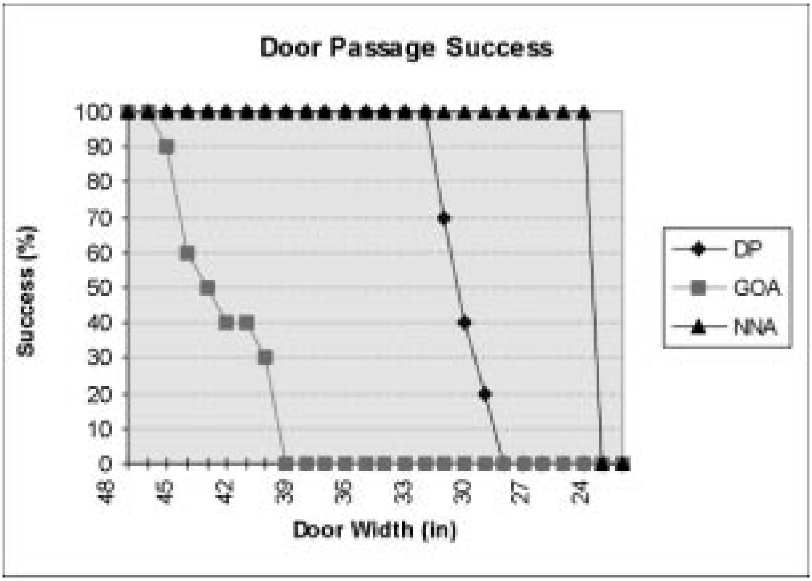

Fig. 7. Results From an Experiment Comparing the Performance of Door Passage Mode, General Obstacle Avoidance Mode, and No Navigation Assistance on a Door Passage Task. DP = Door Passage Mode, GOA = General Obstacle Avoidance Mode, NNA = No Navigation Assistance.

4.3 Automatic Wall Following (AWF) 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 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 to the closest detected obstacle, which allows the NavChair to stop before a collision occurs.

Figure 8 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 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, AWF mode, and without navigation assistance in a hallway traversal task [11]. In this experiment an able-bodied subject 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

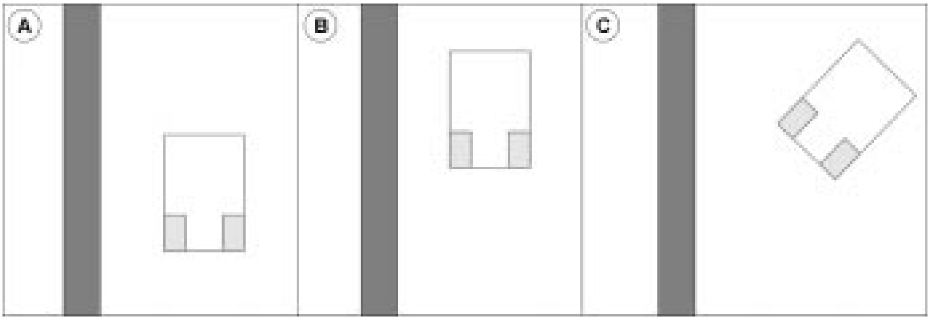

Fig. 8. Automatic Wall Following Mode. Panel A shows a situation which is appropriate for the NavChair to use AWF mode. If the user continues to direct the chair along a path roughly parallel to the wall, the NavChair will follow the direction of the wall (Panel B). However, if the user directs the chair in a direction sufficiently different from the wall, the NavChair will leave AWF mode and move away from the wall. 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.

moved the NavChair down the hallway by pointing the joystick at a 45 degree 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. The results of the experiment are shown in Table 3.

Table 3. 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

Measure	Automatic Wall Following	General Obstacle Avoidance	No Navigation Assistance
Average Time (sec)	9.13	11.27	4.6
Average Speed (mm/sec)	763.90	630.99	1447.17
Average Minimum Obstacle Clearance (mm)	407.38	556.56	322.25

As can be seen from the results of this experiment, AWF mode allows the NavChair to travel at a faster speed closer to a wall than GOA mode can but does not allow the chair to travel as fast or as close to the wall as is possible for an able-bodied operator using the chair without navigation assistance. However, AWF is expected to provide a measureable improvement in performance for the

NavChair's target user population, which is defined by their inability to operate a power wheelchair without navigation assistance.

5 Mode Selection and Automatic Adaptation

5.1 Introduction

The presence of multiple operating modes 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 present unreasonable demands for others. Alternatively, a method for the NavChair to automatically select the correct operating mode on its own has been developed [11]. This method combines information from two distinct adaptation methods. The first, Environmentally-Cued Adaptation (ECA), is based on information about the NavChair's immediate surroundings. The second, Location-Based Adaptation (LBA), is based on information from a topological map of the area in which the NavChair is located.

5.2 Combining ECA with LBA

Information from ECA and LBA is combined using a probabilistic reasoning technique known as Bayesian networks [12]. Bayesian networks use probabilistic information to model a situation in which causality is important, but our knowledge of what is actually going on is incomplete or uncertain. Bayesian networks can be thought of as a means of organizing information to allow the convenient application of a form of Bayes' theorem:

$$\Pr(H \mid e) = \frac{\Pr(e \mid H)\Pr(H)}{\Pr(e)}$$

where, in our applications, H represents the NavChair's operating modes, e is the set of observations, $\Pr(e \mid H)$ represents the probability of observing the most recent evidence given that a particular operating mode, and $\Pr(H \mid e)$ represents the probability that a particular operating mode is the most appropriate operating mode given the available evidence.

Because Bayesian network reasoning is based on probabilistic information, they are well-suited for dealing with exceptions and changes in belief due to new information. An additional advantage is that a network's architecture and internal values provide insight into the nature and connections of the information sources being used to derive conclusions. While none of this precludes the use of other methods, it does make Bayesian networks an attractive option.

Figure 9 shows the Bayesian Network which is used to combine LBA information with that from ECA . For computational efficiency, the Bayesian network is not explicitly represented within the NavChair. Instead, the Bayesian network is "reduced" to a series of parametric equations that receive evidence vectors as input and produce the belief vector for the Correct Operating Mode node as output. Part of the process of reducing the Bayesian network is converting the multiply-connected network in Figure 9 to the equivalent singularly-connected network in Figure 10.

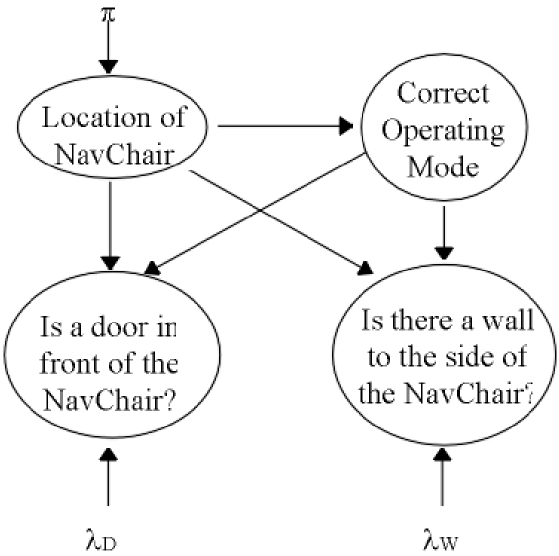

Fig. 9. Bayesian Network Used for Adaptation Decisions in The NavChair

To facilitate understanding, Table 4 contains explanations of all of the symbols used in the following explanation of the Bayesian network. The prior probability vector, π, contains the probability of being in each of the locations specified in the internal map. The two posterior evidence vectors, λ_D and λ_W, contain the probabilities of observing the current sonar signals (in other words, the observed evidence, e given that the environment contained either a door or a wall ($\Pr(e \mid Door = TRUE)$ and $\Pr(e \mid Wall = TRUE)$), respectively).

Table 4: Symbols Used in Explanation of Bayesian Network

Symbol	Type	Name	Explanation
π	vector	Prior Probability Vector	Contains the probability of being in each of the locations specified within the topological map.
λ_D, λ_W	vector	Posterior Evidence Vector	Contains the conditional probabilities of observing the most recent sonar readings given that there is a door/wall in front of the NavChair.

Table 4: (continued)

Symbol	Type	Name	Explanation
e	vector	Observed Evidence Vector	The most recent set of sonar readings.
$\pi(LM)$	vector	Prior Probability Vector	Contains the probabilities that the current location is l_a and the current operating mode is m_b for all combinations of locations $(l_1, \ldots, l_i)$ and operating modes $(m_1, \ldots, m_j)$.
l_a	scalar	Location	The a^{th} of i $(1 < a < i)$ possible locations specified by the NavChair's topological map.
m_b	scalar	Operating Mode	The b^{th} of j $(1 < b < j)$ total operating modes.
$M_{D\|LM}$	matrix	Conditional Probability Matrix	The conditional probability matrix for the Door node (see Figure 10). Each element of the matrix represents the probability of the sonar sensors finding a door given a particular location (l_a) and operating mode (m_b).
$M_{W\|LM}$	matrix	Conditional Probability Matrix	The conditional probability matrix for the Wall node (see Figure 10). Each element of the matrix represents the probability of the sonar sensors finding a wall given a particular location (l_a) and operating mode (m_b).
$M_{M\|L}$	matrix	Conditonal Probability Matrix	The conditional probability matrix for the Correct Operating Mode node (see Figure 10). Each element of the matrix represents the probability of a particular operating mode (m_b) being the correct operating mode given that the NavChair is in a particular location (l_a).
$\pm d$	probabilistic variable	Door/No Door	A door is (not) observed by the sonar sensors.
$\pm w$	probabilistic variable	Wall/No Wall	A wall is (not) observed by the sonar sensors.
e^+	set	Prior Evidence	Evidence used to determine what location the NavChair is in.
e^-	set	Observed Evidence	Sonar sensor readings.

Table 4: (continued)

Symbol	Type	Name	Explanation
$\lambda_D(LM)$	vector	Evidence Vector	Contains the probability of observing the most recent sonar evidence pertaining to the presence of a door in front of the NavChair given all combinations of locations $(l_1, \ldots, l_i)$ and operating modes $(m_1, \ldots, m_j)$.
$\lambda_W(LM)$	vector	Evidence Vector	Contains the probability of observing the most recent sonar evidence pertaining to the presence of a wall to the side of the NavChair given all combinations of locations $(l_1, \ldots, l_i)$ and operating modes $(m_1, \ldots, m_j)$.
$BEL(LM)$	vector	Belief Vector	Contains the probability that the location is la and the correct operating mode is mb given all combinations of locations $(l_1, \ldots, l_i)$ and operating modes $(m_1, \ldots, m_j)$.
$BEL(M)$	vector	Belief Vector	Contains the probability that the correct operating mode is mb for all operating modes $(m_1, ..., m_j)$.
L	set	Set of All Locations	Contains all locations $(l_1, \ldots, l_i)$ specified by the topological map.

Every time the NavChair makes an adaptation decision, the location of the NavChair in the internal map is used to construct the π vector, and the output of the processes for identifying doorways and walls from the NavChair's sonar sensors are used to create the λ_D and λ_W vectors.

Evaluating the network in Figure 10 requires the specification of three conditional probability matrices, one for each node. The conditional matrix for the Door node takes the form:

$$M_{D|LM} = \begin{bmatrix} \Pr(+d \mid l_1 m_1) & \Pr(-d \mid l_1 m_1) \\ \vdots & \vdots \\ \Pr(+d \mid l_i m_j) & \Pr(-d \mid l_i m_j) \end{bmatrix} \tag{1}$$

where $\Pr(+d \mid l_1 m_1)$ represents the probability of observing a door (+d) given that the NavChair is in location 1 (l_1) out of i possible locations and the correct operating mode is m_1 out of j possible operating modes.

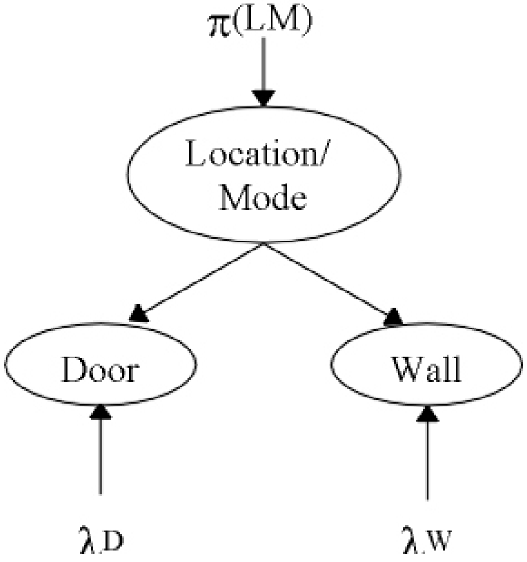

Fig. 10. Equivalent Bayesian Network Used for Mode Decisions

The conditional matrix for the Wall node is of the form:

$$M_{D|LM} = \begin{bmatrix} \Pr(+w \mid l_1 m_1) & \Pr(-w \mid l_1 m_1) \\ \vdots & \vdots \\ \Pr(+w \mid l_i m_j) & \Pr(-w \mid l_i m_j) \end{bmatrix} \tag{2}$$

and can be interpreted similarly to the conditional probability matrix for the Door operating node.

Finally, the conditional matrix for the Mode node which is combined with the Location node in Figure 10 is also needed:

$$M_{M|L} = \begin{bmatrix} \Pr(m_1 \mid l_1) & \cdots & \Pr(m_j \mid l_1) \\ \vdots & \ddots & \vdots \\ \Pr(m_1 \mid l_i) & \cdots & \Pr(m_j \mid l_i) \end{bmatrix} \tag{3}$$

where $\Pr(m_1 \mid l_1)$ represents the probability that m_1 is the correct operating mode given that the NavChair is in location l_1, again out of j possible modes and i possible locations.

The process of making a mode decision in the NavChair proceeds as follows:

1. The system updates the contents of λ_D and λ_W based on the probability of obtaining the most recent sonar data if a door was in front of the chair, $\Pr(e \mid D)$, and the probability of obtaining the most recent sonar data if a wall were to the right or left of the chair, $\Pr(e \mid W)$.

$$\lambda_D = \begin{bmatrix} \Pr(e^- \mid +d) \\ \Pr(e^- \mid -d) \end{bmatrix} \tag{4}$$

and

$$\lambda_D = \begin{bmatrix} \Pr(e^- \mid +w) \\ \Pr(e^- \mid -w) \end{bmatrix} \tag{5}$$

2. The system updates the contents of π based on the location of the chair. If the chair is in location k within the map,

$$\begin{aligned} \pi &= \left[\Pr(l_1 \mid e^+) \cdots \Pr(l_1 \mid e^+)\right]^T \\ &= [0 \cdots 010 \cdots 0]^T \end{aligned} \tag{6}$$

where the k^{th} element of π is 1.
3. The effects of the observed evidence are propogated upwards towards the Location/Mode node. The vector from the Door node is calculated by:

$$\begin{aligned} \lambda_D(LM) &= M_{D|LM} \bullet \lambda_D \\ &= \begin{bmatrix} \Pr(e_D^- \mid l_1 m_1) \\ \vdots \\ \Pr(e_D^- \mid l_i m_j) \end{bmatrix} \end{aligned} \tag{7}$$

Similarly, the vector from the Wall node is calculated to be

$$\begin{aligned} \lambda_W(LM) &= M_{W|LM} \bullet \lambda_W \\ &= \begin{bmatrix} \Pr(e_W^- \mid l_1 m_1) \\ \vdots \\ \Pr(e_W^- \mid l_i m_j) \end{bmatrix} \end{aligned} \tag{8}$$

4. The effects of the prior evidence are propogated downward to the Location/Mode node.

$$\begin{aligned} \pi(LM) &= \pi \bullet M_{M|L} \\ &= \begin{bmatrix} \Pr(l_1 m_1 \mid e^+) \\ \vdots \\ \Pr(l_i m_j \mid e^+) \end{bmatrix} \end{aligned} \tag{9}$$

5. The belief vector for the Location/Mode node is calculated based on the prior and observed evidence by the following formula:

$$\begin{aligned} BEL(LM) &= \alpha \bullet \pi(LM) \bullet \lambda(LM) \\ &= \alpha \bullet \pi(LM) \bullet [\lambda_D(LM) \bullet \lambda_W(LM)] \\ &= \begin{bmatrix} \Pr(l_1 m_1 \mid e) \\ \vdots \\ \Pr(l_i m_j \mid e) \end{bmatrix} \end{aligned} \tag{10}$$

6. The belief in each mode is then calculated from the Mode/Location belief vector:

$$BEL(M) = \begin{bmatrix} \sum_{L=1}^{i} \Pr(lm_1 \mid e) \\ \vdots \\ \sum_{L=1}^{i} \Pr(lm_j \mid e) \end{bmatrix} \tag{11}$$

7. The NavChair's operating mode is then chosen based on which element of BEL(M) has the highest value.

The final detail to be discussed is the selection of values for the conditional probability matrices. These values are filled in beforehand based on the environment in which the NavChair is operating and the nature of the task that it is expected to perform. When the NavChair moves between different environments, or the task(s) it is expected to accomplish changes, then the values of these matrices must be changed as well. There is currently no mechanism for the NavChair to automatically determine the values for these matrices.

5.3 Empirical Evaluation

The NavChair's automatic adaptation mechanism must meet several design criteria [13], the most important being that the method must make the correct operating mode decision as often as possible. In two experiments [11], the NavChair's automatic adaptation mechanism (ECA+LBA) performed better than ECA alone and compared favorably to an expert human making adaptation decisions.

Another important criterion is that the NavChair avoid frequent mode changes, which could lead to an uncomfortable ride for the operator. The NavChair's adaptation mechanism contains built in controls that limit the frequency with which it can change modes, which limit the possibility that it will rapidly switch between different operating modes.

Decisions must also be made in real-time. When in use, the NavChair's automatic adaptation mechanism does not interfere with normal operation of the wheelchair. In particular, the low number of collisions experienced during experiments implies that the NavChair was able to devote most of its computational resources to providing navigation assistance to the operator rather than making adaptation decisions.

6 Discussion

The NavChair has yet to be formally evaluated in trials involving individuals from its target user population. However, feedback has been sought from clinicians active in wheelchair seating and mobility during all phases of the NavChair's design, and an informal session with a potential user provided encouraging results. In our experience, when a standard wheelchair joystick is used to control the NavChair, the effects of the NavChair's navigation assistance tends to improve the performance of individuals that have difficulty operating a power wheelchair but tends to hinder the performance of individuals that do not have difficulty operating a power wheelchair. The primary reason that navigation assistance interferes with skilled driving performance is the tendency for navigation assistance 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 much greater minimum distance from obstacles than is strictly necessary.

Future work is planned in several areas. First, there is a need to add additional operating modes to the NavChair. A close approach mode is already envisioned which will allow a user to "dock" the NavChair at a desk or table. The NavChair is also an attractive testbed for exploring alternative wheelchair interfaces. The NavChair can be used to examine the effects of different input (voice) and feedback (auditory and visual) options that are currently unavailable on standard power wheelchairs.

There still remains much work to be done on the NavChair's automatic adaptation mechanism. In particular, additional information sources need to be identified and incorporated into the existing Bayesian network. One likely information source is user modeling. Some work [9] has already been performed in this area which must be expanded upon before it can be included in the Bayesian network. There is a need to add additional operating modes to the NavChair. A close approach mode is already envisioned which will allow a user to "dock" the NavChair at a desk or table.

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 on its 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.

Finally, there is a need for formal testing of the NavChair with individuals with disabilities. This will require that the NavChair be modified to accommodate the multitude of seating and positioning hardware that members of its target user population 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.

References

1. S. Levine, Y. Koren, and J. Borenstein. The navchair control system for automatic assistive wheelchair navigation. In *Proceedings of the 13th Annual RESNA Conference*, pages 193–194, Washington, D.C., 1990. RESNA.
2. L. Jaros, D. Bell, S. Levine, J. Borenstein, and Y. Koren. Navchair: Design of an assistive navigation system for wheelchairs. In *Proceedings of the 17th Annual RESNA Conference*, pages 379–381, Las Vegas, NV, 1993. RESNA.
3. J. Borenstein and Y. Koren. Noise rejection for ultrasonic sensors in mobile robot applications. In *Proceedings of the IEEE Conference on Robotics and Automation*, pages 1727–1732, New York, 1992. IEEE Press.
4. J. Borenstein and Y. Koren. Histogramic in-motion mapping for mobile robot obstacle avoidance. *IEEE Transactions on Robotics and Automation*, 17(4):535–539, 1991.
5. J. Borenstein and Y. Koren. The vector field histogram - fast obstacle avoidance for mobile robots. *IEEE Journal of Robotics and Automation*, 7(3):278–288, 1989.
6. J. Borenstein and U. Raschke. Real-time obstacle avoidance for non-point mobile robots. In *Proceedings of the Fourth World Conference on Robotics Research*, pages 2.1–2.9, Pittsburgh, PA., 1991.
7. D. Bell, S. Levine, Y. Koren, L. Jaros, and J. Borenstein. An assistive navigation system for wheelchairs based upon mobile robot obstacle avoidance. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 2018–2022, New York, 1994. IEEE Press.
8. D. Bell, S. Levine, Y. Koren, L. Jaros, and J. Borenstein. Design criteria for obstacle avoidance in a shared-control system. In *Proceedings of the RESNA International Conference*, pages 581–583, Washington, D.C., 1994. RESNA.
9. D. Bell. *Modeling Human Behavior For Adaptation in Human Machine Systems.* PhD thesis, University of Michigan, 1994.
10. D. Bell, S. Levine, Y. Koren, L. Jaros, and J. Borenstein. Shared control of the navchair obstacle avoiding wheelchair. In *Proceedings of the RESNA International Conference*, pages 370–372, Washington, D.C., 1993. RESNA.
11. R. Simpson. *Improved Automatic Adaptation Through the Combination of Multiple Information Sources.* PhD thesis, University of Michigan, 1997.
12. E. Charniak. Bayesian networks without tears. *AI Magazine*, 12(4):50–63, 1991.
13. R. Simpson, S. Levine, and H. Koester. Using probabilistic reasoning to develop automatically adapting assistive technology systems. In *Proceedings of the AAAI Fall Symposium on Developing AI Applications for People with Disabilities*, pages 104–108, Boston, MA, 1996. AAAI.