DESIGN CRITERIA FOR OBSTACLE AVOIDANCE IN A SHARED-CONTROL SYSTEM

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Abstract
The NavChair assistive navigation system was originally conceived as an application of mobile robot obstacle avoidance to a power wheelchair. In this system, the user shares wheelchair control with obstacle avoidance and other navigation components. The philosophy of shared control has important implications for the design of these components. This paper discusses the development of a new obstacle avoidance routine for the NavChair guided by design criteria for shared control systems.

Introduction
The NavChair assistive navigation system (1) is being developed to improve the mobility and safety of people who have sensory, perceptual or motor impairments that limit their ability to operate a power wheelchair. The NavChair control systems is designed to avoid obstacles, travel safely through doors and provide other forms of navigation assistance under the direction of the wheelchair user.

The NavChair is a human-machine system in which the user and machine must share control (2). The user is responsible for high-level control of the system, such as route-planning and some navigation actions, while the machine overrides unsafe maneuvers through autonomous obstacle avoidance and can provide addition assistance such as automatic wall following. The user indicates the desired direction and speed of travel with a standard joystick. Various navigation routines modify this command, if necessary, to provide safety and/or improved navigation through a combination of slowing the chair and changing its direction of travel. The system attempts to change the user's command as little as possible while insuring safe, effective travel.

In addition to jointly determining the motor command, the user and the NavChair must be able to cooperatively adapt to changes in environmental or function conditions. Human users adapt rapidly and naturally but machines must be programmed to adapt in response to changes in measurable variables. This makes human-machine co-adaptation difficult, because it requires that the machine monitor user adaptation in real time.

Our attempts to understand cooperative adaptation in the NavChair have lead to design criteria for control system components. The application of these criteria has revealed faults in the original robotic obstacle avoidance method and guided the development of a new obstacle avoidance technique. The following section outlines some of our previous work related to shared control and the development of design criteria. We then apply these criteria to the redesign of the obstacle avoidance component of our system and briefly describe the operation of the new algorithm we have developed.

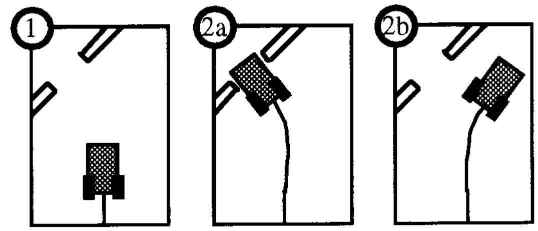

Figure 1: Mode Selection: Frame (1) shows the NavChair approaching a doorway. One of two outcomes is possible: either (2a) the NavChair performs door-passage behavior. or (2b) the NavChair performs an avoidance maneuver. These two behaviors correspond to two modes of operation, door-passage and obstacle avoidance. that cannot be performed simultaneously.

To make this discussion of cooperative adaptation concrete, we will discuss the scenario depicted in figure 1 in which the NavChair must select between two mutually exclusive modes of operation on the basis of measurable variables. In this case, environmental variables are not sufficient to determine mode selection because the presence of a door doesn't always imply that the user wishes to travel through it. The decision to change modes must also be based upon the behavior of the user.

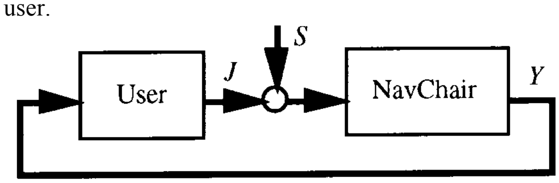

Figure 2: Stimulus Response Modeling:
Observations of responses to an applied stimulus, S, are used to model the behavior of the user. The stimulus perturbs the motion of the wheelchair, Y. which evokes a response in the joystick command from the user, J.

We have developed a new method of automatic mode selection in response to changes in user behavior (3). This method, called "Stimulus Response Modeling," (patent pending) allows the NavChair to qualitatively monitor changes in user behavior and to adapt to these changes in real time (figure 2). We have implemented stimulus response modeling to help the NavChair perform automatic mode selection it, the scenario described above. Essentially, the wheelchair begins with the default hypothesis that the user wishes to continue in obstacle avoidance mode and turns slightly to the right to avoid a collision with the wall. If the user responds by attempting to correct this path deviation in a way that is coherent and consistent with past door-passage

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behavior, then the NavChair automatically selects door-passage mode and proceeds through the door. In this way, the machine adapts to changes in user behavior.

Methods

Design Criteria

The following design criteria, which are derived from the philosophy of adaptive shared control, guided the design of the NavChair's control system:

1. The system should be able to perform the entire range of desired behavior and to control adaptation of the machine.
2. The system must be able to adapt smoothly. For example, mode transitions must be stable and intuitive for the user.
3. The degree of autonomy of control system components should be variable and independently controllable.

The use of stimulus-response modeling imposes additional constraints:

4. The system must be able to measure disturbances in control loops that involve the user. If no external disturbances are present in the system, this implies that the system must be able to apply disturbances that do not interfere with system performance.
5. The user must have a feeling of control in each control loop. For example, in the NavChair, the user must feel that small changes in the joystick command (steer and forward speed) result it, corresponding changes in wheelchair motion.

Redesigning the Obstacle Avoidance Algorithm

The robotic obstacle avoidance method that was originally ported to the NavChair system was developed for use in specialized, fully autonomous systems. As the result, this algorithm, the Vector Field Histogram (VFII) method (4), is not compatible with three of the criteria listed above: 1) It does not provide effective door passage capabilities; 2) The degree of autonomy it, the system is fixed (at full autonomy); and 3) Substantial changes it, joystick position often have no effect on wheelchair motion. Our original attempts to port the VFH method for use in the NavChair have been described elsewhere (5). However, the application of the above criteria represents a fundamental change in control philosophy and has resulted in further changes that improve the performance of the NavChair system.

The operation of the original and modified VFH methods are outlined in figures 3 and 4. The original VFH method is fully autonomous in the sense that the system is designed to select the obstacle-free direction closest to the target direction specified by the user. The user can often move the joystick without producing any change in the behavior of the wheelchair. Our new method trades obstacle avoidance against the goals of the user, providing greater and more variable control to the user. We call the new method "Minimum VFH" (MVFH).

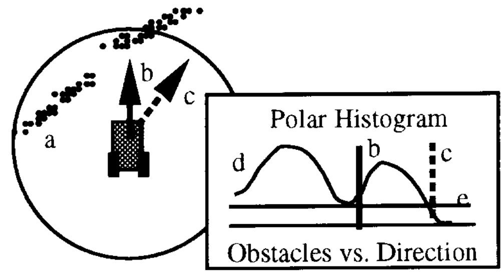

Figure 3: VFH Obstacle Avoidance: In the scenario from figure 1, sensor readings arc used to update a map of obstacles in the form of a certainty grid ((1). The certainty grid is used to calculate a polar histogram (d) in which high values represent close and/or large obstacles. The target direction specified by the user (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).

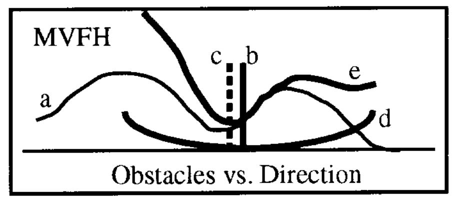

Figure 4: MVFH Obstacle Avoidance: Both VFH and MVFH use the polar histogram (a) to calculate the direction of travel. MVFH minimizes the sum (e) of the polar histogram and a weight function (d) of the distance to the target direction (b) to find a satisfactory trade-off (c). Currently this function is a parabola that allows obstacle avoidance to make small command modifications relatively easily while making large changes more difficult. In this case, MVFH centers the NavChair in the doorway, represented by the "valley" in the histogram.

MVFH provides variable component autonomy ii, the following sense: 1) When the target-direction weight function is a very steep parabola compared to the obstacle-density histogram, obstacle avoidance will have almost no effect on the direction of travel; 2) When the weight function is flat, the wheelchair will be effectively autonomous. Because the shape of the target weight function can be changed in real time, the autonomy of the system can be adapted to meet the instantaneous needs of the user.

Design Criteria for Shared-control Systems

MVFH does not guarantee that the wheelchair will always move in an obstacle-free direction. For these cases we have added a collision-prevention routine that slows the chair by an amount proportional to the square root of the distance to the nearest obstacle in the direction of motion. This routine smoothly decelerates the wheelchair to a stop a specified distance from obstacles. With high autonomy, the wheelchair goes around obstacles with little decrease in speed, while low autonomy allows the user to drive the wheelchair close to obstacles and through doors. Therefore, NavChair control modes can be changed by adjusting the autonomy of the obstacle avoidance. For example, the transition from obstacle avoidance to door passage is effected by simply lowering the autonomy of obstacle avoidance to allow the user to select a path towards the door.

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Results

We have found that the Minimum VFH method provides safe, effective door-passage for the NavChair. Figure 5 compares experimental results of door-passage success for the original and Minimum VFH methods. Ten trials were made at door widths from 0.7 to 1.2 meters. The ratio of successful to attempted passages was recorded for each width. Success was defined as passage without the need for user intervention due to perceived blockage. MVFH is more successful at door passage than VFH because it allows the NavChair to move closer to obstacles (the door posts) and because it naturally tends to center the chair as it approaches the doorway. The original method merely avoids each of the door posts.

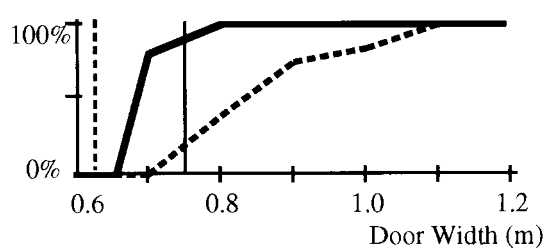

Figure 5: Door Passage Test Results: Percentage of successful door passage versus door width for VFH (dashes) and MVFH (solid). Two vertical marks provide scale: 1) dashed: the NavChair is 0.63 m wide; and 2) solid: standard doors are 0.76 m wide.

Discussion

The conformity of the MVFH method with the design criteria discussed above allows the advantages of the VFH method to be extended to a shared-control system: 1) Safe and effective door passage is possible with MVFH; 2) The level of autonomy of the obstacle avoidance is completely variable and controllable; and 3) Changes in joystick position always result in changes in wheelchair motion.

The design criteria presented above were developed in the context of the NavChair system. However, we hope that this discussion will benefit other researchers who are experiencing similar difficulties in other applications of rehabilitation engineering. In addition, this research has implications for the design of a broad variety of human-machine systems. For example, an ability to design systems capable of seamless human-machine cooperative adaptive on would allow automobiles to automatically select "sport" and "economy" modes for better mileage and acceleration than non-adaptive designs.

Many rehabilitation technologies are developed as autonomous components. This research suggests that the design of human-machine control system components is substantially different than for autonomous systems. An awareness of the differences in design philosophy between autonomous and shared-control systems is necessary for the development of the best possible rehabilitation technologies and to facilitate the integration of autonomous components into effective human-machine systems.

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