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Abstract

We describe the development and assessment of a computer controlled wheelchair equipped with a suite of sensors and a novel interface, called the SMARTCHAIR. The main focus of this paper is a shared control framework which allows the human operator to interact with the chair while it is performing an autonomous task. At the highest level, the autonomous system is able to plan paths using high level deliberative navigation behaviors depending on destinations or waypoints commanded by the user. The user is able to locally modify or override previously commanded autonomous behaviors or plans. This is possible because of our hierarchical control strategy that combines three independent sources of control inputs: deliberative plans obtained from maps and user commands, reactive behaviors generated by stimuli from the environment, and user-initiated commands that might arise during the execution of a plan or behavior. The framework we describe ensures the user's safety while allowing the user to be in complete control of a potentially autonomous system.

Comments

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Incorporating User Inputs in Motion Planning for a Smart Wheelchair

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***Abstract*— We describe the development and assessment of a computer controlled wheelchair equipped with a suite of sensors and a novel interface, called the SMARTCHAIR. The main focus of this paper is a shared control framework which allows the human operator to interact with the chair while it is performing an autonomous task. At the highest level, the autonomous system is able to plan paths using high level deliberative navigation behaviors depending on destinations or waypoints commanded by the user. The user is able to locally modify or override previously commanded autonomous behaviors or plans. This is possible because of our hierarchical control strategy that combines three independent sources of control inputs: deliberative plans obtained from maps and user commands, reactive behaviors generated by stimuli from the environment, and user-initiated commands that might arise during the execution of a plan or behavior. The framework we describe ensures the user's safety while allowing the user to be in complete control of a potentially autonomous system.**

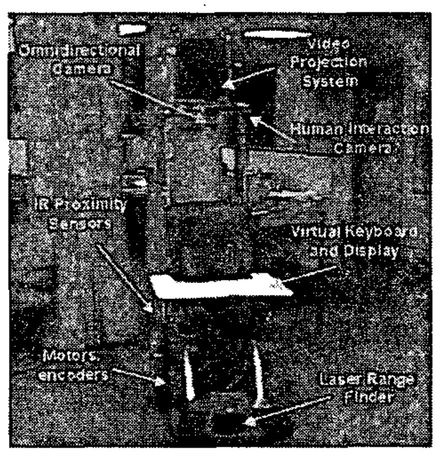

Fig. 1. The GRASP Laboratory SMARTCHAIR

I. INTRODUCTION

There are numerous examples of partially autonomous systems in which the low level controllers are autonomous while the human user is primarily responsible for decision making at the higher levels. An important class of these systems are mobile agents with embedded computers that are directly controlled by a human pilot or navigator in the control loop. The user's ability to interact with embedded computers, actuators, and sensors influences the performance of such human-in-the-loop systems [1], [2].

Our main focus in this article is on smart wheelchairs (Fig. 1), devices that can potentially benefit over 5 million individuals in the U.S. alone [3]. Current systems have very little computer control; interfaces are similar to those found in passenger cars. The rider has to continuously specify the direction, and in some cases, the velocity of the chair using a joystick-like device. In cases where the level of neuro-muscular control is poor, joysticks are used to specify directions while the choice of speed is limited to a safe constant value.

There is extensive research on computer-controlled chairs where sensors and intelligent control algorithms have been used to minimize the level of human intervention [4], [5], [6], [7]. There are a number of research groups that have developed novel robotic wheelchairs. Wheelchair researchers have taken different approaches to incorporate human inputs into the control loop. One strategy is to allow the user to command directions to the chair directly and use the autonomous system for ensuring safety by avoiding obstacles [8]. Another is to have the wheelchair perform specified behaviors, such as following a person or tracking a line [9], [10], [11], [12], [13]. At an even higher level, it is beneficial to be able to automatically navigate to locations on a map [14], [15]. At this level, landmarks or known targets are used to navigate to the desired location [16], [17], [18].

The goal of the research presented here is to find a solution to the motion planning and control problem that allows us to incorporate deliberative plans with reactive behaviors. The reactive behaviors of interest to us come from two separate categories. The two types of dynamic/reactive constraints are unmodeled obstacles and unpredictable human inputs. In our work, we illustrate a human-in-the-loop motion planning and control framework that is used for human robot augmentation in an assistive technology. We systematically bring together three diverse, and at times contradictory, goals in motion planning: deliberative, reactive, and user-initiated. The incorporation of user input is particularly important for assistive technology. We experimentally show that we are able to plan deliberative paths, use reactive controllers for safety, and integrate human inputs into our smart wheelchair system. We illustrate the ease with which a human user can interact with the SMARTCHAIR, allowing the user to intervene in real time during the execution of an autonomous task. This flexibility allows the human user and the autonomous system to truly share control of the system.

In this paper, we first briefly describe the SMARTCHAIR platform and the system model. In Section III, we discuss our computer-mediated motion planning and control framework. We begin by generating a deliberative plan using the potential field method. We combine the deliberative plan with local reactive behaviors and then we explicitly introduce the human user into the system. Section IV provides experimental results which illustrate the performance and benefits of the human augmented system. Finally, Section V contains a discussion of our conclusions and future work.

II. THE SMARTCHAIR

Our motorized wheelchair is equipped with onboard processing and a suite of sensors as seen in Fig. 1. The omnidirectional camera, mounted over the user's head, allows the user to view 360 degrees around the wheelchair. The projector system displays images onto the laptray and enables the user to send commands to the wheelchair through a visual interface. The projector and camera systems act in concert forming a feedback system where the user interaction is effected by occluding various parts of the projected image.

Along with the vision system, there is a laser scanner, which is mounted in the front of the wheelchair, under the user's feet. The laser measures distances at every half degree through a 180 degree scan. Similarly, the IR Proximity sensors are placed on the back of the chair to detect any obstacles located behind the wheelchair. Lastly, encoders on the motors provide a dead reckoning system for the wheelchair. The wheelchair platform is discussed in greater detail in [19].

A. System Model

We model the chair as a two-wheeled, nonholonomic cart-like robot. The governing equations are well-known [20]:

$$\begin{aligned} \dot{x} &= v\cos(\theta) \\ \dot{y} &= v\sin(\theta) \\ \dot{\theta} &= \omega, \end{aligned} \tag{1}$$

where the input $u = [v, \omega]^T$, consists of the forward velocity, v, and angular velocity, ω, while (x, y) are the coordinates of the center of the wheel axle in an inertial frame. θ is the angle that the wheelchair coordinate system forms with the inertial frame. As seen in Fig. 2, generally, we describe features (obstacles, targets, etc.) by (f_i, z_i), where f_i is the angle in this case and z_i is the corresponding range.

III. SHARED CONTROL FRAMEWORK

In most assistive devices, the operator and the robot must share control of the system. While humans are able to bring experience and global knowledge, a robot is able to help increase precision and reduce fatigue when assisting in tasks. We have developed a computer-mediated motion planning and control framework that allows the human user to share control with the robotic assistive technology on various levels. Our system has three types of input signals: goal-oriented, u_ϕ, human commanded, u_h, and obstacle avoidance, u_g. Each of these is a 2×1 vector function, $u(t)$, which appears in Eq. 1.

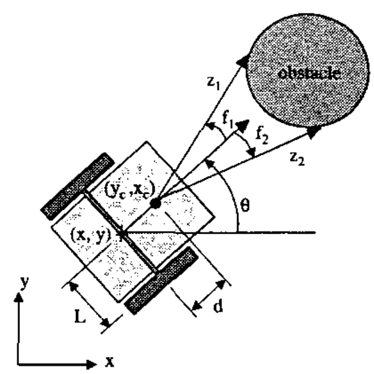

Fig. 2. Model of the system. (x, y) is the coordinate of the midpoint of the axle while (x_c, y_c) is the point that is being controlled.

We will see that at every instant, each vector will define a half-space in R^2, which we will denote by U_ϕ or U_g. We will compute the feasible set, F, as the intersection of the appropriate half spaces.

A. Deliberative Motion Plan

Motion planning approaches can be broadly divided into two categories, deliberative and reactive approaches. Deliberative approaches use global information and are generally open loop. Local feedback information is used in reactive approaches, which are closed loop. In order to obtain a deliberative motion plan, we would like to use a global navigation function. However, it is difficult to compute this instantaneously, so instead, we compute an approximate navigation function by using dynamic programming on an occupancy grid. The occupancy grid is based on known obstacles, such as walls and tables, from a map of the environment. Since this does not satisfy all the properties of a navigation function, it is called a potential function. However, in contrast to previous work where potential field controllers are called reactive, because the construction of this function assumes a map of the environment, we call the resulting controller a deliberative behavior.

When using the potential field method, a scalar field $\phi(q)$ is defined over the free space. $\phi(q)$ is called the potential function. To reach the desired goal, the robot must follow a motion plan that satisfies the constraint $\dot{\phi}(q) \leq 0$. This constraint is satisfied when the robot moves along the negative gradient of the potential, $-\nabla\phi(q)$. Thus, the controller used in this method is:

$$\dot{q} = -\nabla\phi(q), \tag{2}$$

where $\dot{q}$ is the velocity vector of the wheelchair given by:

$$(\dot{q}) = \begin{pmatrix} \dot{x}_c \\ \dot{y}_c \end{pmatrix} = \begin{pmatrix} \cos\theta & -d\sin\theta \\ \sin\theta & d\cos\theta \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix}. \tag{3}$$

By combining Eq. 2 and Eq. 3, we obtain the control law as follows:

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = -\begin{pmatrix} \cos\theta & -d\sin\theta \\ \sin\theta & d\cos\theta \end{pmatrix}^{-1} (\nabla\phi). \tag{4}$$

Using a map of the environment we assign an "attractive potential" to the goal position and a "repulsive potential" to known obstacles. A vector field is defined over the configuration space by taking the negative gradient of the sum of the two potentials. So for each position in the configuration space we have defined a $-\nabla\phi(q)$, which is used to control the robot.

In fact, $-\nabla\phi(q)$ is not the only control input that moves the robot to the goal. Any control input in the same half space of $-\nabla\phi(q)$ is a feasible controller [21]. So, as seen in Fig. 3, U_ϕ is the half space which contains all of the configurations that the robot can assume that satisfy "the potential field constraint." This is exploited in the following sections to combine reactive behaviors and human inputs with a deliberative motion plan.

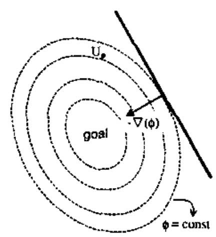

Fig. 3. U_ϕ is the half plane consistent with the deliberative motion plan.

B. Deliberative Plan with Reactive Behaviors

The next level of our framework involves combining a deliberative plan with local, reactive behaviors. We assume that the robot has a map of the environment that includes static obstacles. However, the robot has no *a priori* knowledge of unmodeled or dynamic obstacles that it may encounter while heading towards the target.

If obstacles are detected within a specified minimum distance around the wheelchair, the obstacle avoidance algorithm may need to be activated. The detection of objects can be done by any of the available sensors. The most basic implementation of this is to place a bound on the distances, (z_1, z_2), as seen in Fig. 2. (f_1, z_1) and (f_2, z_2) are extreme readings from the obstacle. If δ is a minimum distance that is required between the chair and an obstacle, then if $|z_i| < \delta$, the chair will switch into obstacle avoidance mode. If an obstacle is encountered, the chair needs to move away from the obstacle while driving towards the desired target given by the deliberative plan. The obstacle acts as a constraint to our deliberative plan, which is represented by g_i. To satisfy this constraint, we need an input that makes $\dot{g}_i \leq 0$, where

$$\dot{g}_i(q(t), t) = \frac{\partial g_i}{\partial q} \cdot \dot{q} + \frac{\partial g_i}{\partial t}. \tag{5}$$

The first term represents the robot's own influence on the obstacle, while the second term takes the dynamics of the constraint into account. We define $g_i = g_i(z_i, f_i)$. So, as z_i increases, $(\dot{g}_i) \leq 0$. Using this constraint, we define a half space, U_g, which contains a set of robot configurations which will not collide into the obstacle. The feasible set is the intersection of the half plane given by the potential field, U_ϕ, and the half plane given by the obstacle constraint, U_g. As seen in Fig. 4, $F = U_\phi \cap U_g$ and the goal is to select an input that makes $\dot{\phi} \leq 0$ (decrease the distance to the goal) as well as $\dot{g}_i \leq 0$ (increase the distance to the obstacle). Any u which exists in the set F is a feasible controller.

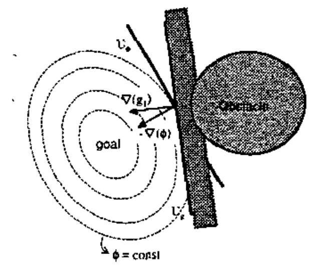

Fig. 4. The feasible region is the intersection of the half planes given by the potential field method and the obstacle-free configuration space.

C. Deliberative Plan, Reactive Behaviors, and Human Inputs

While the robotic system needs to comply with dynamic constraints, any unpredictable human inputs given to the system also need to be taken into consideration. Besides configuration space constraints, there are also other constraints that need to be accounted for, which are specific for human-in-the-loop systems. When combining human inputs with deliberative plans and reactive behaviors, we need to set up a hierarchical, prioritized framework. We would like the human user to maintain control of the system, while keeping our first priority of safety. By adding a virtual bumper on the wheelchair and in the environment, we are able to prevent collisions from occurring. We also incorporate an obstacle avoidance algorithm that allows the system to circumvent any unmodeled, dynamic obstacles that may appear in the path.

When the human user manually inputs a command, we have various methods of handling the input. In the simplest case, we can allow the user to have complete control of the wheelchair. In this situation, u_h is the commanded signal from the user and the controller is simply defined as $u = u_h$.

However, since safety is one of our top priorities, we realize that it is important to combine user-initiated inputs with local obstacle avoidance. If the user is manually driving the wheelchair and comes across an obstacle, there are two methods that will allow us to avoid a collision, either drive around it or stop. Before either of these are done, the first step is to check if the user's input, u_h, will result in a collision. As seen in Fig. 5 (left), if the human input is in the feasible half plane, U_g, then the controller is simply, $u = u_h$. Since the user is not trying to enter a constrained region, we allow him or her complete control similar to the case without any obstacles. However, if the user's input is located in the obstacle constrained region, then we need to either stop moving or give the user partial control. In Fig. 5 on the right, the user's input is located in the constrained region. In the constrained region, there is a threshold that determines if the system should stop or if it should continue its motion. If the user input is in the constrained region, but outside of the stopping region, then the user is allowed partial control of the motion. Partial control is given by projecting the human input onto the boundary of the obstacle constraint. This allows the chair to move partially in the direction specified by the user while also avoiding the obstacle. Thus, Eq. 6 permits the user to keep limited control of the wheelchair without a collision.

$$u = (u_h \cdot \hat{t})\hat{t} = ||u_h|| \cos\beta\hat{t} \tag{6}$$

$$\hat{t} = \frac{\nabla g_i^{\perp}}{||\nabla g_i^{\perp}||} \tag{7}$$

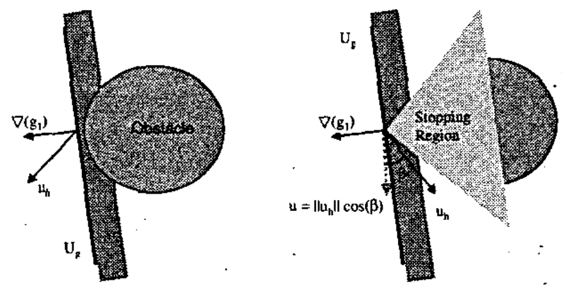

Fig. 5. Human input is consistent with half plane given by the obstacle-free configuration space (left). On the right, although the user's input is within the constrained region, by projecting the input into the feasible region, we allow the user to maintain limited control of the wheelchair without a collision.

Along with combining human inputs with local behaviors, we are also interested in combining user inputs with a deliberative plan. In this case, the user has selected a desired target that he or she wants to reach. While using a deliberative plan to reach the goal, the user may decide to deviate from the path to perform a subtask. If the user's input is consistent with the goal, i.e. $u_h \subset U_\phi$, then we allow the user to maintain complete control of the wheelchair, $u = u_h$, as seen in Fig. 6. If the user's input is not consistent with the goal, then, similar to the obstacle constraint, there are two options available. The first is to modify the user's input to conform with the goal. Figure 6 (right) illustrates the case where the human input is within the goal constrained region, and is projected to the boundary of the feasible half plane. This allows the user to have limited control of the wheelchair while conforming with the potential field controller. The controller, $u = (u_h \cdot \hat{t})\hat{t}$, modifies the human input, u_h, by projecting it to the tangent of the potential field line, thereby keeping the robot motion consistent with $\dot{\phi} \leq 0$, which means the goal has not been abandoned. If the user is persistent, i.e. the input is beyond a threshold, then the goal is disregarded and the human possesses full control of the chair. The threshold can be an angular boundary, as seen in Fig. 6 (right). We realize that the deliberative constraint is not a physical barrier like an obstacle, and therefore give more flexibility and control to the user. In an attempt to combine the human input with the deliberative goal, we have placed an configuration space threshold on the system.

The final task is to combine all three goals in motion planning for a human robot assistive technology: human inputs, deliberative plans, and reactive behaviors. By expanding

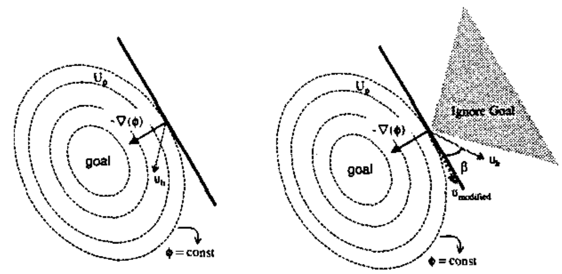

Fig. 6. The feasible region is the half plane containing $-\nabla\phi(q)$ (left). On the right, the human input occurs outside of the feasible region and is modified to conform with the goal constraint.

on Fig. 4, which illustrates the configuration space available when combining a potential field boundary with an obstacle avoidance constraint, the user's inputs are added into this system. As long as the user's input is contained in the feasible space we allow the human to intervene and take control of the motion. In other words, $u = u_h$ if $u_h \in U_\phi \cap U_g$.

However, when the user's input is not consistent with either the goal-oriented motion plan or the reactive obstacle avoidance, or even both, we apply the rules previously described in this section. We compare the user's input with the goal-oriented motion plan and either modify the input or drop the goal constraint, preserving the user's input. Then, the resultant input is compared with the obstacle avoidance constraint. If necessary, the input is again modified to preserve the safety of the user. This allows the user maximum control while preventing collisions (Fig. 7).

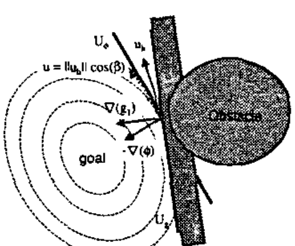

Fig. 7. Although the user input is not in the feasible space, the modified controller, u, gives the user limited control while preventing collisions.

IV. Experimental Results

In this section we show how the shared control framework is used for navigation and present experimental results that illustrate the performance of the system as well as the main benefits of augmentation. We consider the three levels—navigating using a deliberative motion plan, combining local, reactive behaviors to the plan, and incorporating user inputs into the system.

We represent ground truth by using overhead markers and odometry from the wheelchair. Simple tests conducted to observe factors that could contribute to irregularities in odometry, such as belt or wheel slippages, reveal that such slip is minimal at low speeds [19]. A system of overhead markers and localization based on an on-board camera helps us eliminate drifts due to errors in dead reckoning.

A. Deliberative Plans

Some typical tasks a wheelchair user may want to perform include approaching and passing through designated doors; going to specified locations in the environment, such as windows or closets; or steering down hallways. We want the user to be able to reach locations on a map by simply clicking a point on the image of a map. Using a deliberative motion plan, our chair can autonomously navigate to the user's desired position. Here we provide an example of a potential function [22], [23] placed on a map of the environment. Figure 8 shows an overhead view of our lab. The dark regions are tables and other known objects in the environment. The lighter region is an expanded map, which takes into consideration the size of the wheelchair and a safety boundary. The expanded map is used for navigation. Figure 9 illustrates an example of a potential field that is generated automatically to the desired target. Figure 10 shows the path followed by the wheelchair when using the potential field controller. As seen in the figure, the chair is guided by the potential field lines to the desired location.

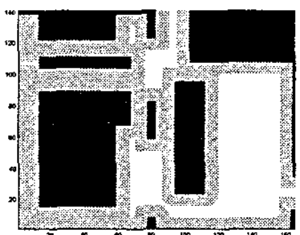

Fig. 8. Overhead map of the environment.

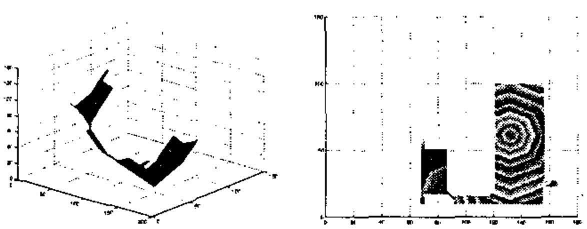

Fig. 9. Potential function map to a desired goal.

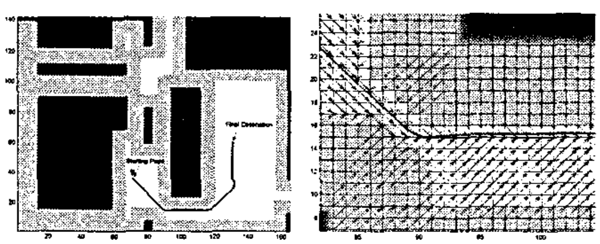

Fig. 10. Trajectory taken by wheelchair using the potential field controller.

B. Deliberative Plan with Reactive Behavior

If the wheelchair encounters obstacles on its way to the target, it switches to an obstacle avoidance controller to circumvent the obstacle before switching back to the potential field controller [21]. In Fig. 11, the target destination remains the same as before, however, the wheelchair encounters unmodeled obstacles along the way. The lighter line segment represents when the obstacle avoidance mode is activated, while the darker line is the trajectory the chair follows using the deliberative plan.

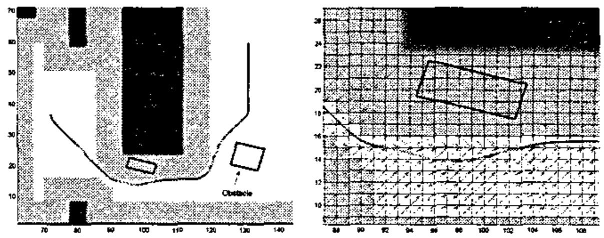

Fig. 11. Trajectory taken by wheelchair using the potential field controller combined with local, reactive behavior.

C. Human Inputs, Deliberative Plan, and Reactive Behavior

When human inputs are incorporated into the system there are different scenarios that may occur. The first case is when there is only a human input with obstacle avoidance. If the human input moves the wheelchair in a direction that is consistent with avoiding obstacles, then the user's input does not get modified. If the human user's command is in conflict with obstacle avoidance, then either the human user's input needs to be disregarded so that a collision can be avoided, or the input is modified (as seen in Fig. 5 (right)). By modifying the user's input, the user maintains partial control of the wheelchair while avoiding the obstacle.

Besides combining human inputs with other local behaviors, we also are able to combine human inputs with a deliberative plan. As the wheelchair is following the potential field lines to move towards the goal, the user inputs a direction that may be either consistent with the goal or in conflict with it. In Fig. 13 part(b), the user's input is consistent with the goal. Here, the path is slightly modified to accomodate the user while still satisfying Eq. 2, which continues to move the chair towards the goal.

Lastly, we combine human inputs with both the deliberative plan and local, reactive behaviors. The basic algorithm (pseudo-code) is shown in Fig. 12.

Figure 13 shows the autonomous system navigating towards the goal using the deliberative plan. However, the user inputs commands while the chair is moving, as seen by the lighter line. Along with the human input, there are unmodeled obstacles in the chair's path. We are able to reconcile all three of these conflicting inputs so that the user is able to maintain partial control of the chair while avoiding collisions and moving towards the goal.

V. Conclusions

In this paper, we present a shared control strategy, that allows us to incorporate human inputs in motion planning for a smart wheelchair. The most significant advantage of the system is the ease with which we are able to combine three diverse, and at times, contradictory, goals in wheelchair

if goal is specified **then**
  $u_\phi := -\nabla\phi(q)$
  if user input **then**
    $\varphi :=$ angle between vector u_h and vector u_ϕ
    if $\varphi > \pi/2$ and $\varphi < \varphi_{limit}$ **then**
      $\overline{u} := (u_h \cdot \hat{u}_\phi^\perp)\hat{u}_\phi^\perp$
    else
      $\overline{u} := u_h$
    end if
  else
    $\overline{u} := -\nabla\phi(q)$
  end if
else if user input **then**
  $\overline{u} := u_h$
end if
if obstacle close **then**
  $u_g := -\nabla(g)$
  $\gamma :=$ angle between vector $\overline{u}$ and vector u_g
  if $\gamma > \pi/2$ and $\gamma < \gamma_{limit}$ **then**
    $\overline{u} := (\overline{u} \cdot \hat{u}_g^\perp)\hat{u}_g^\perp$
  else if $\gamma > \gamma_{limit}$ **then**
    $\overline{u} := 0$
  end if
end if
Use $\overline{u}$ as control input for the wheelchair

Fig. 12. Algorithm for combining deliberative plans, reactive behaviors and human inputs.

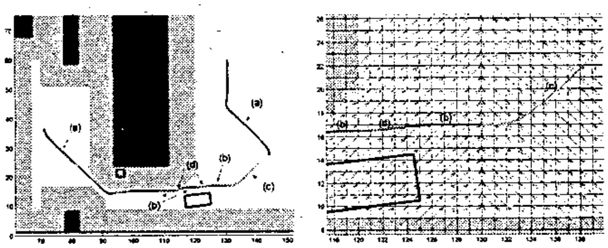

Fig. 13. Trajectory taken by wheelchair using a deliberative plan, combined with user input along with obstacle avoidance. Part(a) represents the deliberative path taken, part(b) represents the user's input, which is consistent with the deliberative plan, part(c) highlights the modified user input, which allows the user partial control of the system, and part(d) represents the obstacle avoidance region.

control. We introduce a deliberative plan on our system by deriving a potential field function from a map of the environment. Next, we combine local, reactive behaviors with the deliberative plan and show that the system is able to efficiently reach the selected goal while avoiding unmodeled, dynamic obstacles. Finally, since we have a human-in-the-loop system, user inputs are added to the system and we experimentally illustrate the benefits of shared control between the user and the autonomous system. We are also able to safely allow the user to maintain partial control of the human-centered assistive device. Our future work is directed toward describing human input and conducting studies with human subjects.

ACKNOWLEDGMENTS

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