A Robotic Walker That Provides Guidance

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Abstract

This paper describes a robotic walker designed as an assistive device for frail elderly people with cognitive impairment. Locomotion is most often the primary form of exercise for the elderly, and devices that provide mobility assistance are critical for the health and well being of such individuals. Previous work on walkers focused primarily on safety but offered little or no assistance with navigation and global orientation. Our system provides these features in addition to the stability and support provided by conventional walkers. This capability is achieved by a software suite of robot localization and navigation combined with a shared-control haptic interface. The system has been tested in a retirement facility near Pittsburgh, PA, USA.

1 Introduction

The elderly population is growing at a dramatic rate and causing a greater demand for devices that extend independent living and promote improved health. Since inactivity among the elderly has been shown to be a significant cause of increased morbidity [1, 2] and premature mortality [3], devices that enable daily exercise are essential to the health and welfare of these individuals. As locomotion is most often the primary form of exercise for the elderly, this segment of the population dominates the users of devices that offer mobility assistance [4]. Despite the dependence on such ambulatory assisting devices, contemporary walkers and subsequent variants only provide assistance with user stability. Navigational assistance, for those who suffer from senile dementia and frequently become disoriented, and motion-control aid, for those who possess deficiencies in motor skills and cannot properly control their walkers, are features not currently available. These forms of aid, while critical to the functionality of the user, are only provided through direct human-to-human interaction.

Escorting the elderly who reside in long term care settings to medical (doctor and therapy appointments), social (meeting friends), and cosmetic (manicure, getting a hair cut) activities, as well as such repetitive daily tasks as visits to dining facilities, is a necessary yet time-consuming task that requires human assistance. With the growing disproportions between the number of residents in nursing homes/assisted living facilities and the staff such facilities [5], the problem becomes clear: staff capacities have already become insufficient for meeting the residents' needs causing tasks like resident escorting to be sacrificed for other, higher-priority duties. Thus, an obvious challenge is to equip walkers with the capabilities to provide orientation and guidance.

Our research builds on a rich body of literature on robotic walkers and assistive devices [6, 7, 8, 9]. These mobility aids have provided safety and stability to their users through means of collision avoidance or velocity/acceleration limits for operation on uneven terrain [6]. Such features have been implemented in powered wheel chairs [8, 9] through local path planning.

One of the first robotic mobility aid to incorporate guidance functionality was the PAMM cane [7]. It performed route following by localizing to unique ceiling markers along a designated path. Although not directly assisting human locomotion, tour-guide robots [10, 11, 12, 13] have been developed by various research groups over the past few years for maturing guidance systems in dynamic environments. Navigation has also been developed in other context as with wearable computing [14]. This technology is leveraged into the present system, which is unique in its use of a haptic interface on a walker to mediate human and robot control.

This paper presents a novel approach to addressing both the mobility needs of the elderly and the service needs of the nursing staff by combining the stability of conventional walkers with the sensing, planning, and navigational capabilities of mobile robotics. Our implementation is built on top of a commercial omnidirectional mobile robot base platform, equipped with two force-sensing handle bars that resemble the grippers of conventional walkers. Forces asserted through this haptic interface are mediated with control from the navigation system in a way that maximizes a person's perceived freedom while still achieving point-to-point navigation. Our navigation system, largely developed in previous research [13, 15, 16] integrates probabilistic techniques for mapping, localization, path planning, and collision avoidance. Mixed modes of user assistance in the form of controlled robot motion and visual cues are examined to assist the user navigate without becoming intrusive to the user's desires. This shared control system

Figure 1: The XR4000 platform with walker handlebars and LCD display.

Figure 2: A map of the testing facility, the Longwood Retirement Resort in Oakmont, PA. This map has been acquired by our mobile robot. It exhibits a range of different areas, such as a dining hall (right) and a conference hall (left).

is implemented on a mobile robotic platform and has been field tested in an assisted living facility with results presented in this paper.

2 Physical System Overview

The physical system is depicted in Figure 1. Our present prototype has been built on top of a Nomad XR4000 mobile robot platform. This robot is equipped with an omnidirectional drive, making it ideal for navigating through corridors in close proximity of a person. The robot is also sturdy enough to supply sufficient physical support to its clients. The 0.61 meter diameter of the robot, however, prohibits navigation through narrow doorways; for this reason our experiments have been confined to hallways and larger doorways.

The robot is equipped with two circular arrays of Polaroid ultrasonic transducers, two circular arrays of Nomadics infrared near-range sensors, three large touch-sensitive doors, and a SICK LMS laser range finder. These sensors enable our system to perceive obstacles at various heights, and the SICK laser range finder is used for navigation (mapping, localization, path planning).

To function as a robotic walker, the platform has been equipped with two handlebars, as shown in Figure 1. Both handlebars are mounted in a fixed position relative to the robot's frame, to provide physical support and stability. The handlebars are also the loci of the haptic interface: Both bars are equipped with two independent force sensors each, enabling the robot to measure forces asserted by the user. The interface provides sufficient information to navigate the robot into arbitrary directions. Additionally, the robot features a visual LCD display panel that informs the user about the system's desired motion direction. The display is similar to existing in-vehicle guidance systems used routinely in the automotive industry [17]. The display is updated several times a second, thereby always providing an accurate assessment of the desired motion direction for reaching a target.

Figure 4 shows a sequence of images recorded with one of our test subjects. This subject is a resident of a retirement facility in Oakmont, PA, our primary testing ground. Our experiments, which will be reported further below, evaluate the effectiveness of our system in real-world situations under the premise that the user is unaware or mentally incapable of knowing her target location. Experiments investigate the feasibility of escorting people through their environments using our robotic walker, and the relative merits of the robot's individual components.

3 Robot Navigation System

The robot's navigation system is built on top of Carmen, which is short for Carnegie Mellon's Navigation Toolkit. Precursors to the Carmen system were used in dozens of robots worldwide, including the two museum tour-guide robots Rhino [12] and Minerva [13]. Building on these systems, Carmen has been developed into a full-fledged software system for autonomous mobile robot navigation in indoor environments. It contains software modules for collision avoidance, localization, mapping, path planning, navigation, and people tracking. Carmen is strictly a probabilistic software system, in that all essential information is represented via probability distributions.

At the core of Carmen's navigation routines are metric environment maps. Figure 2 depicts such a map taken from a retirement facility in Oakmont, PA, USA. The map represents an occupancy grid maps [18] with a resolution of 10 cm. It has been acquired in real-time using the probabilistic mapping software described in [19]. During the mapping process, environment size is significant. The robot is manually driven through the environment using a joystick interface and, within

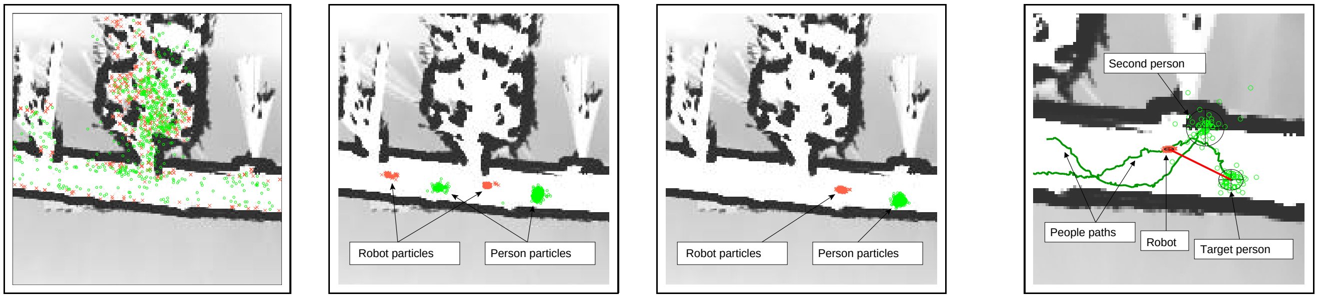

Figure 3: (a)-(c) Evolution of the conditional particle filter from global uncertainty to successful localization and tracking. (d) The tracker continues to track a person even as that person is occluded repeatedly by a second individual.

Figure 4: (a) The robotic walker, as it escorts an elderly person. (b) The haptic interface for controlling the walker. (c) The walker's display provides simple directions (in form of an arrow) as to where to move for the present target location.

a few minutes, a map is produced. Potential target locations are subsequently marked manually in these types of maps. The entire process takes no more than 30 minutes, making our robot system extremely portable to new environments.

A core competency of the software system is its ability to always possess an accurate estimate of the robot's location relative to its environment. This is achieved through a fast version of Monte Carlo localization [15], a popular technique for probabilistic mobile robot localization based on particle filters [20]. Since the robot has to function in the proximity of people, Carmen utilizes a conditional particle filter algorithm that enables it to track people by detecting differences between actual measurements and the map [16]. As a result, Carmen is not only aware of its own location, but also of that of nearby people. Knowledge of the latter also improves the robot's ability to localize itself, since it enables the robot to identify measurements that are corrupted by people—a major problem of localizing mobile robots in dynamic environments [21]. Figure 3 shows a sequence of estimates of a globally uncertain robot, as it gradually localizes itself. This sequence, reprinted with permission from [16], illustrates the robot's ability to effectively estimate people's positions in the proximity of the robot. In practice, our system is always informed of the initial starting pose, so that localization errors remain bounded.

On top of the robot's perceptual routines, Carmen offers additional software for navigating robots. This software was originally designed for autonomous mobile robot navigation and was modified to accommodate a shared-control user interface, as discussed further below. Carmen's navigation modules integrate real-time fast collision avoidance with the ability to plan (and modify) global paths to arbitrary target locations within the map. The path planning module calculates a sequence of via-points in 2D space which minimize the overall path length while maintaining clearance to nearby obstacles. This set of via points is calculated dynamically, based on the map, the target location, and the robot's present location. As a result, deviations from the prescribed robot path are easily accommodated by recalculating new via points. The via-points are then translated into actual robot motion commands by a fast, local controller [22]. This controller minimizes the time it takes to reach a via point, under the constraints imposed by the dynamics of the robot. Collision avoidance is achieved by dynamically incorporating all sensor measurement at the control level. As a result, the robot is capable of moving smoothly from any location to any other location in the environment while avoiding collisions with obstacles, both static and dynamic. We notice that the maximum speed supported by Carmen is well in excess of 50 cm/sec, which exceeds the walking speed of elderly people by a large margin.

4 Shared Control Interface

Shared control is an essential component in the development of a robotic walker. The robot must be capable of providing

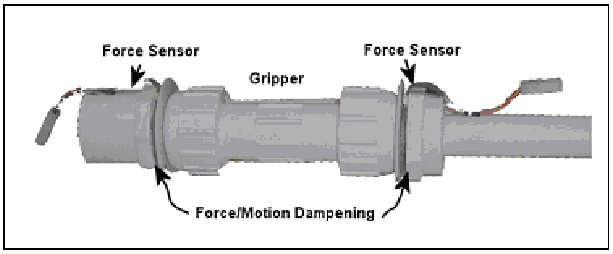

Figure 5: The haptic interface handlebars.

navigation and guidance while maintaining a natural and predictable motion response. As addressed in [6], the concept of shared control describes a system where two or more independent control systems function concurrently to achieve common goals. The focus of this work attempts to bind the control of two systems (an elderly human and a robotic walker) engaged in the task of navigation. Since the goals of human and robot may often misalign, the shared control system must determine whether the human or the machine cedes control. The two components enabling shared control are a haptic interface for capturing user intent and the control software that binds the two systems.

4.1 Haptic Interface

The haptic interface is a means of registering the user's intention through physical interaction. The interface transforms the force applied by the user into the robot's motion. Devices like buttons, joysticks, and levers already exist for relaying user input; however, they require hand displacement that would loosen or otherwise release the user's hold. Such interfaces make operation very difficult and potentially unsafe. In addition, the elderly who use contemporary walkers are fully aware of the walker functionality and expect a specific response from input force. Utilizing the user's preconceived notion of how a walker should operate is critical to a haptic interface design.

For this work, the haptic interface consists of force sensors that were embedded into the handlebar structure of the walker robot. Handlebars provide the support and stability in ambulatory devices and require the user's hands to grip firmly. By incorporating force sensors inside the handlebars, the user can maintain a steady hold and manipulate the robotic walker in a manner more consistent with contemporary roller-based walkers. The haptic interface used in the proceeding experimental trials is shown in Figure 5. Each handlebar is equipped with a prismatic handgrip that is motion constrained. Semi-pliable foam is inserted between the handgrip and motion stops to dampen the displacement exhibited by the grippers. A pair of force-sensing resistors (one mounted on each motion stop) is embedded into the foam to detect pressure when force is exerted along the handlebar. These pressure readings are transformed into planar translational and rotational velocities. In an attempt to keep the control of the robot as intuitive as possible, a forward push on both the handle bars results in a forward motion, while a differential push-pull combination results in a rotary motion. However, a pull on both the handle bars stalls the robot. In the following section, the means of integrating user stimuli with the robot's navigational planner is addressed.

4.2 Control Software

The control software combines raw force data with robotic navigation to produce the motion of the robot. To achieve reliable and predictable motion from a self-mobile robot, human and machine control must be tightly coupled. Unlike the shared control systems presented in previous robotic research [6], coordination of a self-mobile system requires a full understanding of the users' intentions and desired actions. Therefore, user-intended trajectory and robot-intended trajectory are key elements in motion deliberation.

User-intended trajectory is determined through a user motion model. This model represents a mapping of force sensor readings recorded from the haptic device to trajectory commands. In this work, these models were constructed from data analysis performed on standard roller-walkers. In this control system, raw data is fetched from the force sensors, filtered, and input into the user motion model to determine the user-desired translational and rotational velocities (Figure 6).

The robot-intended trajectory is acquired through the navigational system using the Carmen software suite. The robot is first localized within the world map and given a goal position. A path from the robot's current location to the goal is then generated. Since the navigation system factors in obstacles, walls, and minimum transversal length, the path is considered the most desirable course for both human and machine.

When user and robot intentions are obtained, the motion of the robot is determined. In this work, three modes of operation define the shared control system:

1) Passive mode: The robot's intended trajectory is ignored, allowing the user to move freely throughout the environment. The robot's primary function in this mode is to prevent collisions with obstacles and monitor user position.

2) Active mode: The robot's intended trajectory is used as the desired system trajectory. The user's estimated trajectory is actively compared to desired trajectory and if a deviation greater than a given reference angle is detected, the robot's motion is slowed. Unless the user realigns with the path, the robot will eventually halt. This mode of operation is accompanied with a graphical interface to assist the user in staying on path.

3) Forced mode: The robot's intended trajectory is used completely. User input is only used as a means of switching robot motion on and off. The user has no control over the direction of the robot and is kept rigidly to the path.

These modes are set when the user begins a navigation task. In future work, mechanisms can be set in place that allow dynamic adjustment of control modes to suit the needs of the user. Similar work in automotive settings has shown that such

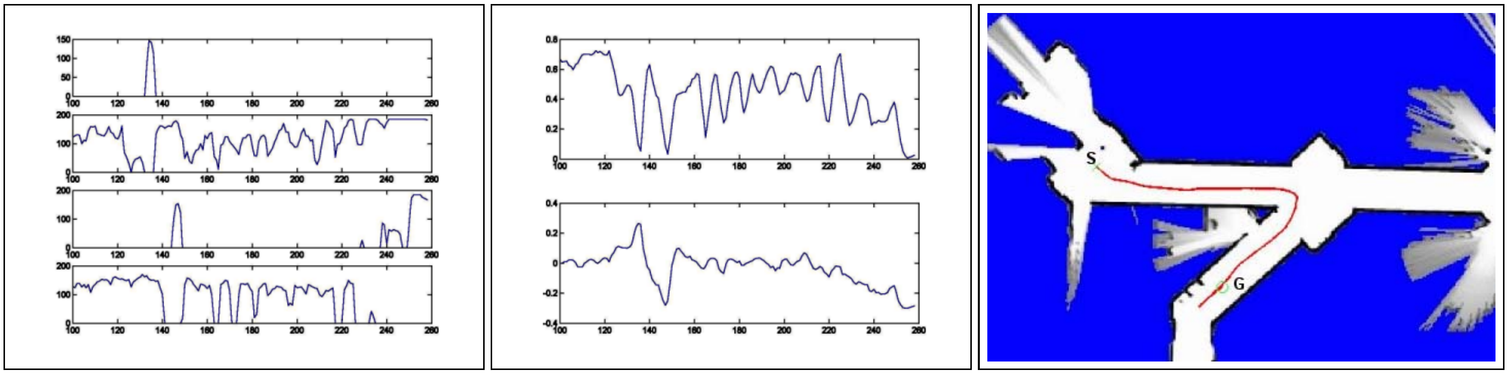

Figure 6: Moving from raw force data to motion. (a) The raw data reading received from the handlebars. From top to bottom, the plots are force readings taken from the back left, front left, back right, and front right sensors. (b) The top shows the translational velocity in m/s and the bottom shows rotational velocity in rad/s (c) The plot of the path created from this data.

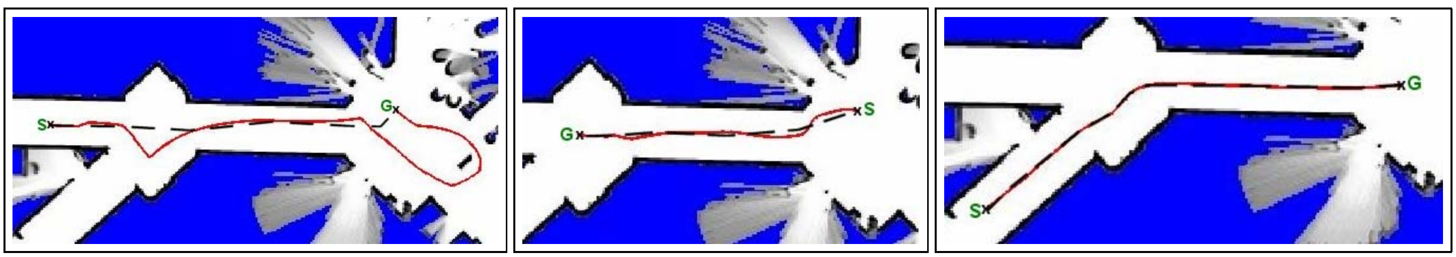

Figure 7: Paths taken by subject under varying modes of mode. In each plot, 'S' indicates the start position and 'G' indicates the goal position. (a) Motion data recorded from passive mode. (b) Motion data recorded from active control. (c) Motion data recorded from forced mode.

dynamic switching can be successful in real-time shared control applications.

5 Experimental Results

Experimental trials of this walker robot system have been performed at a retirement facility in Oakmont, PA, USA. Four residents of the facility were asked to operate the walker in a navigation task under the various modes of control. Their trajectory data and haptic input were logged along with the robot's trajectory input and projected path. The system was evaluated on its usability and capacity to keep the user moving toward the goal.

The motion response of the system can be seen in Figure 7. For each mode of control, the user was informed to move to a goal position. Under passive control, large path deviations were witnessed (Figure 7a) since the navigational system offered no intervention. Under active control, the motion of the user was restricted to within 80 degrees of the intended orientation. The result was that the user was forced to remain much closer to the path producing minimal deviation (Figure 7b). Finally, the user was required to operate under forced control. As projected, the robot remained rigidly along the intended path, delivering the user directly to the goal (Figure 7c).

User acceptance and interest in the robotic walker was high with several points of feedback. At first, some users had difficulties manipulating the haptic interface; however, they were able to quickly adapt when instruction was provided. The robot's peak velocity was set at 0.5 m/s, allowing residents to choose a comfortable pace.

After preliminary tests held at Carnegie Mellon University, a user interface was implemented to assist in directing motion. It was discovered that the participant became confused during active control whenever the robot stopped suddenly. Visual feedback was displayed on a laptop LCD screen and consisted of a large rotating arrow that pointed in the direction of the next waypoint. If the user was oriented in the correct direction, the arrow pointed up; likewise, if the user began to drift, the arrow would rotate towards the next desired location. By seeing the arrow, the participant was fully aware of the robot's intended trajectory. In many cases, the visual representation was critical to effective navigation since it provided communication between robot and human. Furthermore, the simplicity of an arrow was found to be far less confusing compared to displaying maps and goal locations.

The results of the walker robot experiments with elderly participants demonstrate and validate the control concepts and technical feasibility of a mobile robotic walker. Through these tests and future experimentation, this work can be used as a prototype platform for robotic walkers that can escort nursing home residents, enable greater social interaction, and improve the overall quality of living for the elderly at such facilities.

6 Summary and Conclusions

This paper presented a novel approach to the design and implementation of a mobility assistant device. By augmenting a commercial mobile robotic platform with haptic sensing, the Carmen navigational system, and a shared control scheme, a robotic walker was developed. Multiple modes of human to robot control were investigated in order to determine the best compromise between user freedom and completing a specified navigation task. This robotic system was then field tested in an assisted living facility with successful results.

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