An Adaptive Shared Control System for an Intelligent Mobility Aid for the Elderly

Article *in* Autonomous Robots · July 2003

DOI: 10.1023/A:1024488717009 · Source: DBLP

Autonomous Robots 15, 53–66, 2003

An Adaptive Shared Control System for an Intelligent Mobility Aid for the Elderly

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Abstract. The control system for a personal aid for mobility and health monitoring (PAMM) for the elderly is presented. PAMM is intended to assist the elderly living independently or in senior assisted living facilities. It provides physical support and guidance, as well as monitoring basic vital signs for users that may have both limited physical and cognitive capabilities. This paper presents the design of a bi-level control system for PAMM. The first level is an admittance-based mobility controller that provides a natural and intuitive human machine interface. The second level is an adaptive shared controller that allocates control between the user and the computer based on metrics of the user's performance. Field trials at an eldercare facility show the effectiveness of the design.

Keywords: adaptive, control, elderly, shared, PAMM

1. Introduction

1.1. Motivation

The elderly populations in many countries are growing rapidly according to the U.S. Department of Health and Human Services (AOA, 2001). For example, persons 65 years or older numbered 35 million in 2000 and represented 12.4% of the US population (AOA, 2001). As people grow older, their physical and cognitive functions degrade. Current practice is to move such an elderly individual into facilities that provide higher levels of care.

Assisted living facilities are generally the first alternative to independent living. These facilities aid their residents with daily activities such as bathing and meal preparation; however, most facilities cannot provide labor-intensive support, such as guidance for the residents that become disoriented frequently. Approximately 30 to 40 percent of assisted living facility residents suffer from some level of senile dementia (ALFA Advisor, 1995). These residents often require assistance with guidance, medication regulation, health-condition monitoring, and scheduling daily activities, see Table 1. When these disabilities progress to the point that the elderly require the constant attention of a caregiver, the transition to a skilled nursing facility is traditionally the only solution. In these facilities, costs are higher and quality of life is often reduced (Burton, 1997). The cost of staying in a skilled nursing facility (often called a nursing home) in major city in the US can easily exceed $90,000 to $100,000 per year compared to less than $40,000 per year for an assisted living facility. Clearly it is cost-effective to keep the elderly out of nursing homes if possible. It is also well known that the transition to a nursing home is a very traumatic experience for many elderly people. Hence there are great social and economical benefits delaying the transition using robotic technology. Smart assistive technology offers the potential solutions to delay the need for individuals to enter nursing homes.

1.2. Background and Literature

There is a growing interest in developing intelligent assistive devices for the elderly. The PAM-AID (Lacey and Dawson-Howe, 1998) is a robotic mobility aid that provides some physical support and obstacle avoidance to frail and blind elderly people. The Hitomi (Mori

Table 1. Typical assisted living facility resident's physical and cognitive needs.

Needs	Deficiencies	Causes
Guidance	Failing memory, disorientation	Senile dementia, Alzheimer's.
Physical support	Muscular-skeletal frailty, instability	Osteoporosis, diabetes, Parkinson's, arthritis, etc.
Health monitoring	Poor cardiovascular potential strokes and heart attacks	Age, lack of exercise, illness (e.g., flu or pneumonia)
Medicine and other scheduling	Need for a variety of medicines coupled with failing memory	Senile dementia, general frailty

and Kotani, 1998) is a robotic travel aid for the blind in outdoor environments. It provides users with orientation and map-based guidance based on information about obstacles and landmarks. The Care-O-bot (Schraft et al., 1998; Graf, 20001; Graf and Hägele, 2001) and the Nursebot (Baltus et al., 2000) are personal service robots developed for the elderly and disabled. The Care-O-Bot is intended to aid mobility, do household jobs, and provide communication and entertainment functions. The Nursebot project has focused on human machine interface methods, tele-presence via the Internet, speech interface, and face tracking. A device called Power-Assisted Walking Support System has been developed at Hitachi to help support elderly people standing up from bed, walking around, and sitting down (Nemoto et al., 1999). A device called Personal Mobility Aid is being developed at University of Virginia (Wasson et al., 2001). It is modified from a standard three-wheeled walker by fitting a steering motor on the front wheel, adding encoders for dead reckoning, and adding laser and IR sensors for obstacle detection. The aim of the project is to help elderly users to steer clear of obstacles. For all these devices, the fundamental problem of providing control to users who have varying levels of training and perhaps diminished mental and physical capabilities remains a challenge.

User interface is critical for these devices. The design must take into consideration the user's characteristics. The users of mobility aids generally have direct physical interaction with the system for support. A key requirement is that the interface should be able to adapt to users with different levels of physical and mental functionality. The interface should provide reliable bilateral communication between the user and the machine to ensure safety. It should also provide a natural feel for the user and be easy for the user to learn to use. Researchers have studied various forms of interfaces. The joystick is widely used for robotic wheelchairs (Levine, 1999; Lankenau and Rofer, 2001). However, for the mobility aids concerned in this paper, where the user and the machine are two dynamic entities, the joystick tends to cause oscillatory motion when users walk with the device (Lacey and MacNamara, 2000). Switches and buttons can be used to select directions or control modes, but they are limited by their discrete nature (Lacey and MacNamara, 2000). They could also increase the mental workload and cause confusion and frustration for the elderly users. Touch screens have also been implemented as an interface for the elderly (Baltus et al., 2000; Schraft et al., 1998). Using voice communication as human machine interface is another area of active research. These can become effective high-level command and bilateral communication tools, but they cannot serve as continuous control interface.

For cooperative robotic devices in industrial applications, where the human operator and the machine have direct physical interaction, force sensing and the related force control strategies are widely used (Al-Jarrah and Zheng, 1997). However, a force sensor itself can not guarantee a good interface. Using force signals directly to generate motion can result in unstable motion due to the fluctuation of the signals. This problem has been encountered in the Care-O-bot project (Graf, 20001; Graf and Hägele, 2001). This paper presents an admittance-based control method that uses the force/torque sensor to provide a natural and intuitive interface for elderly users.

A major challenge of the control system development is how to allocate the control between the user and the machine. A shared control system integrates the best capabilities of both the human and the machine. Humans are best at high level cognitive tasks such as object identification, error handling and recovery, use of heuristics and common sense in the presence of uncertainty. On the other hand, machines have high mechanical and computational power, and good accuracy. A substantial amount of work has been done in the shared autonomy and cooperative control for tele-operations, space, and aviation systems (Sheridan, 1992). Many researchers are developing shared control strategies for assistive devices. Various methods of shared control design of power wheelchairs are reviewed in Cooper (1995). In these control strategies, there are a few preset discrete behavior modes using fuzzy logic or probabilistic models, such as wall following, passing doorways and obstacle avoidance. The shared control methods are used to select from one of them based on the obstacle sensor information and user input. Methods have also been developed to make the shared control system adaptive to different tasks and situations for a wheelchair (Levine et al., 1999; Simpson and Levine, 1999). Obviously, these few behavior modes can limit the freedom of the user.

In summary, substantial research with significant progress has been done on the control of robotic and telerobotic systems and vehicles. However, the important problem of identifying the capabilities of the operator, particularly when the user may have diminished mental and physical capabilities, and then adjusting his authority to ensure safe system operation based on those capabilities remains unsolved. This problem is addressed in this paper in the context of the PAMM systems, which are described below.

2. The PAMM Systems

A series of robotic aids, called PAMMs (Personal Aids for Mobility and Monitoring), have been developed in the Field and Space Robotics Laboratory at MIT to assist the elderly in assisted living facilities and delay their transition to nursing homes (Dubowsky et al., 1997; Godding, 1999; Spenko, 2001; D'Arrigo, 2001).

Working with several assisted living facilities in the Boston Area, a set of performance goals have been established for the PAMM concept, see Table 2.

Table 2. PAMM system level performance goals.

Potential users	Elderly with mobility difficulty due to physical frailty and/or disorientation due to aging and sickness.
Environment	Assisted living facilities. Known structured indoor environment with random obstacles such as furniture and people. Flat and relatively hard floor or ramps less than 5 degrees.
Physical stability	Provide equal or better stability than that of a standard four-point cane or walker.
Guidance and obstacle avoidance	Provide guidance to destinations via pre-programmed maps, schedules, user commands, and sensed obstacles.
Health monitoring	Provide continuous health monitoring.
Communication	Provide two-way communication with centralized computer.

Figure 1 shows the PAMM concept. The PAMM can be either a cane or walker. It has a six-axis force-torque sensor mounted under the user's handle to serve as the main user interface. An admittance-based controller integrates the user input signals with the instruction of the schedule based planner, the facility map information, and signals from the obstacle avoidance sensor in order to control the system. On-board sensors monitor the user's basic vital signs. The system communicates via a wireless link with a central computer in order to receive up-dated planning information and to provide information on the health and location of the user. The location of PAMM is determined from a CCD camera which reads passive signposts placed on the ceiling of the facility.

Two PAMM configurations have been developed to meet the needs of both cane and walker users. The cane configuration is called SmartCane and is shown in Fig. 2. The walker configuration is called SmartWalker

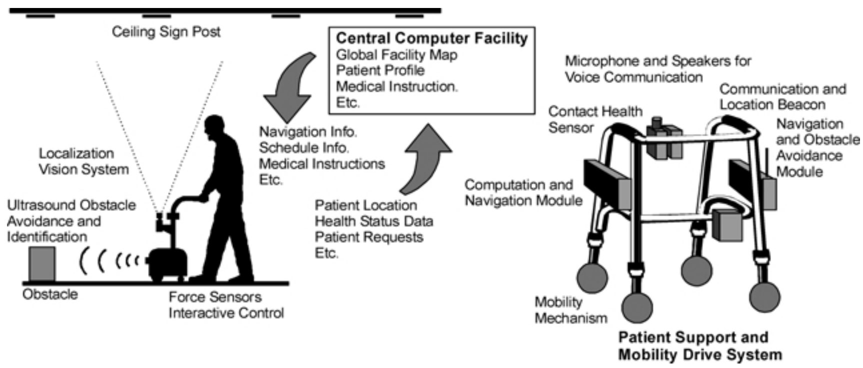

Figure 1. PAMM system concept.

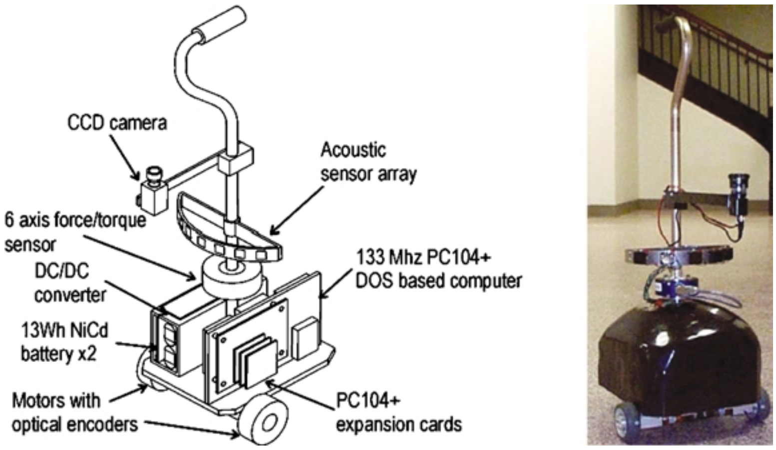

Figure 2. PAMM SmartCane prototype.

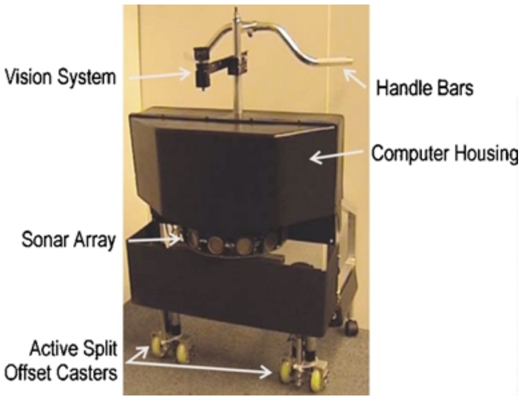

Figure 3. PAMM SmartWalker prototype.

and is shown in Fig. 3. A walker gives the user substantially more physical support than a cane. It has basically the same computer, electronic, and sensor systems as the SmartCane. The mobility design of the SmartCane uses skid steering. While this is acceptable for the SmartCane as it is relatively small in size, the nonholonomic constraint of such a system is not suitable for the SmartWalker. An omni-directional mobility using the active split offset castor (ASOC) has been developed for the SmartWalker (Yu et al., 2000; Spenko et al., 2002).

This paper focuses on the control of the PAMM, and in particular the user interface. This interface should be able to determine the intent of the user even in the presence of the user's confusion. The controller gives the user as much control as possible, but it ensures user safety by adjusting the control authority based on the demonstrated performance of the user. It must be noted that the development of control algorithms for human machine systems is less analytical and precise than that for completely determined systems and autonomous control. The development and evaluation of the control system of PAMM depends largely on experimental work carried out with the elderly in the eldercare facilities.

The control of PAMM has two levels. The lower level is the user interaction control based on the admittance-based control methodology. The higher level is the adaptive shared controller for the control allocation between the user and the machine. These two levels are described in the following sections.

3. The PAMM Admittance Control Development

3.1. Concept of Admittance-Based User Interaction Control

The six-axis force/torque sensor attached to the PAMM handle is used as the main control input interface. Through it the user has continuous control of the system. The force/torque sensor signals are interpreted for motion control by using an admittance controller (Durfee et al., 1991). The admittance model emulates a dynamic system and gives the user a "feeling" as if he is interacting with the system specified by the model.

The admittance of the modeled dynamic system is defined as a transfer function with the user's forces and torques, $\mathbf{F}(s)$, as input and the PAMM's velocities, $\mathbf{V}(s)$, as the output. It is expressed as:

$$\mathbf{G}(s) = \frac{\mathbf{V}(s)}{\mathbf{F}(s)} \tag{1}$$

The reciprocal transfer function is called impedance, which is the basis for the widely used concept of impedance control. The response of the PAMM is obtained by solving the dynamic equations in real time, and solving the inverse kinematics of the physical system to get the desired actuator velocity. The admittance control approach allows the PAMM dynamics to be set like a linear or nonlinear system, subject to limitations of actuator power, servo control bandwidth, and computation limitations. Models with fast dynamics require higher bandwidth and fast sampling time for the control system. Complex models obviously require more computation power. However, these do not appear to be significant issues for devices for slow moving elderly people.

The admittance-based interaction control for PAMM is shown in Fig. 4. Users of PAMM interact with PAMM through the force/torque sensor. Signals from the force/torque sensor contain not only the user's intention but also the support, stability, and gait information of the user. The signals from the force sensor first go through a transformation so that the driving forces and the support force at the handle are extracted. The support force, which points downward, is not used to generate motion directly, but is used for stability analysis and as a condition to start or stop the motion. It was found in field experiments that a few users generated unintended forces which are coupled with the driving forces. For example, some users of the SmartCane initially generated an unintentional twisting torque at the handle. However, with some practice they developed good control of the cane. Driving forces are also filtered before the admittance model to eliminate high frequency noise. The admittance model can be changed for each individual user. The states of the system, such as velocities, are monitored and used to change the dynamic model so that the control is variable.

The PAMM SmartCane has two degrees of freedom, one for forward motion in the Y direction, and the other for rotation around the Z direction. The PAMM SmartWalker is omni-directional and has 3 degrees of freedom. Hence admittance models with two and three DOF mass-damper systems have been implemented on the SmartCane and SmartWalker respectively. A linear 2 DOF mass-damper model for the SmartCane is defined as:

$$\begin{bmatrix} M_y & 0 \\ 0 & J_z \end{bmatrix} \begin{bmatrix} \dot{v}_y \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} B_y & 0 \\ 0 & B_z \end{bmatrix} \begin{bmatrix} v_y \\ \omega \end{bmatrix} = \begin{bmatrix} F_y \\ M_z \end{bmatrix} \tag{2}$$

In the forward direction, the system emulates a plant of a mass M and damping B, as illustrated by Fig. 5. With F as the user input force in the forward direction and V as the system response in the same direction, the transfer function of the system is:

$$G(s) = \frac{V(s)}{F(s)} = \frac{1}{Ms + B} \tag{3}$$

The time response of the system for a step input is:

$$v(t) = \frac{F}{B}(1 - e^{-t/\tau}) \tag{4}$$

where τ is the time constant defined by $\tau = M/B$. The steady state velocity of the system is $V_{ss} = F/B$.

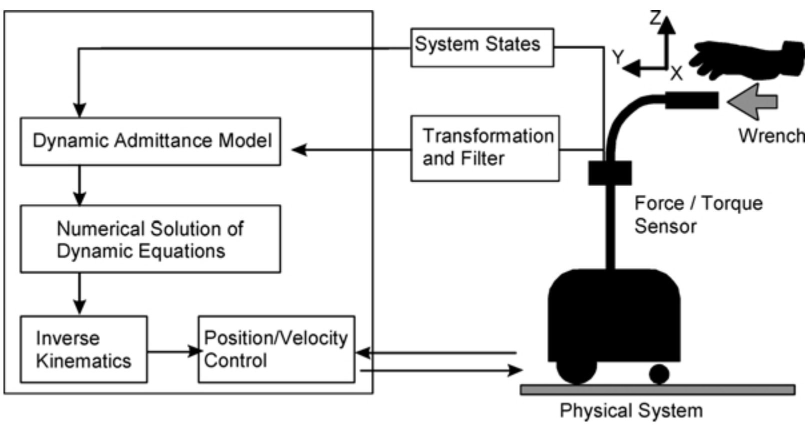

Figure 4. Admittance-based human-machine interaction control.

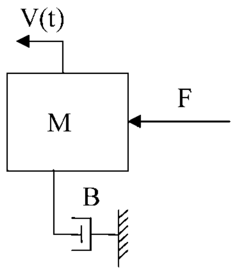

Figure 5. A Mass-damper admittance model.

3.2. *Experimental Study of the Admittance-Based Control*

The challenge in the design of the admittance controller was found in determining the appropriate model (M and B), choosing a metric to evaluate the performance of the model, and optimizing the dynamics to minimize operator effort. These question can only be answered with experiments with the actual users through field trials. In the process of PAMM development, extensive experiments have been conducted for both the SmartCane (Godding, 1999) and SmartWalker with elderly residents at an assisted living facility (Yu, 2002).

First, a series of tests were conducted to evaluate the general usability of PAMM with the admittance control. Figure 6 shows typical results of the PAMM SmartWalker driven by an elderly user. The admittance model has M and B as 14 Kg and 40 Ns/m respectively. It shows that the user walks at an average speed of about 0.25 m/s. The average driving force (F_y in the forward direction) is about 12 N. Because the mass-damper model also acts as a low pass filter, high frequency noise due to shock and vibration from the floor and the hand tremor of the user are reduced. The driving force signal has some high frequency noise, but PAMM's speed is quite smooth with a lower frequency variation that corresponds to the user's gait. It also shows that the forward driving force and the downward support force are in concert, meaning the user gets good support walking with the SmartWalker. The support force for the user is in the range of 40 N to 70 N. This is very close to the forces measured on a conventional wheeled-walker by the researchers of the Care-O-Bot (Graf, 2001).

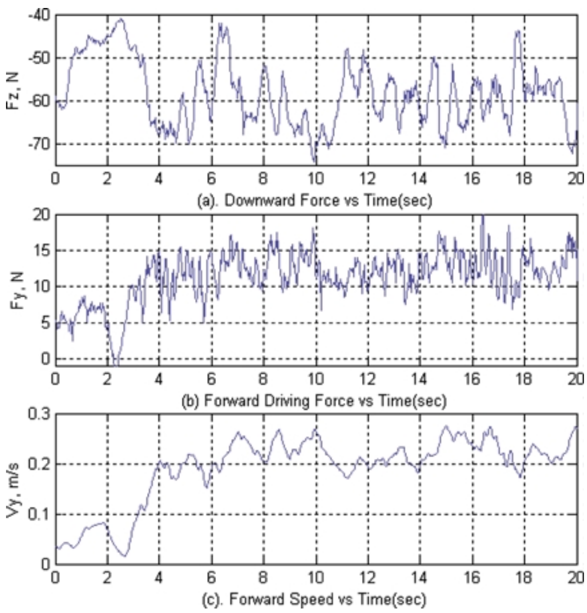

Figure 6. Example of the PAMM admittance control response.

To study the acceptance of PAMM and to help select the values of the admittance model (M and B), questionnaire surveys were used in the field experiments as a qualitative measure. Users were asked to drive PAMM freely at the facility and compare PAMM with their conventional mobility aids. Issues on ease of control, how heavy it felt to drive, ease of learning, physical support, and overall acceptance of PAMM as a mobility aid were evaluated using a five point scale rating. The evaluation result of the PAMM SmartCane is presented in Godding (1999). Figure 7 shows the result of the tests of the PAMM SmartWalker by a group of eight users. The model used for these tests has a mass M of 14 Kg and a damping B of 60 Ns/m. The figure shows the highest, average, and lowest ratings given by the users on each issue. Although the average ratings are relatively high on every issue, the variations suggested that different users require different system parameters. To determine the effects of M and B, nine models with different mass and damping combinations were tested with the SmartCane. The values of M used are 2.5, 5, and 10 Kg, and the values of B are 10, 20, 30 Ns/m. From the tests, the effects of different mass and damping combinations have been identified, as shown in Fig. 8. For models with small mass and damping, the motion is oscillatory because the model is too responsive. For models with small mass and high damping, which have small time constant, the motion is also oscillatory, this time it is due to high frequency noise. For models with large mass and small damping, the motion is difficult to control as the inertia is too large; users felt that they were dragged along when

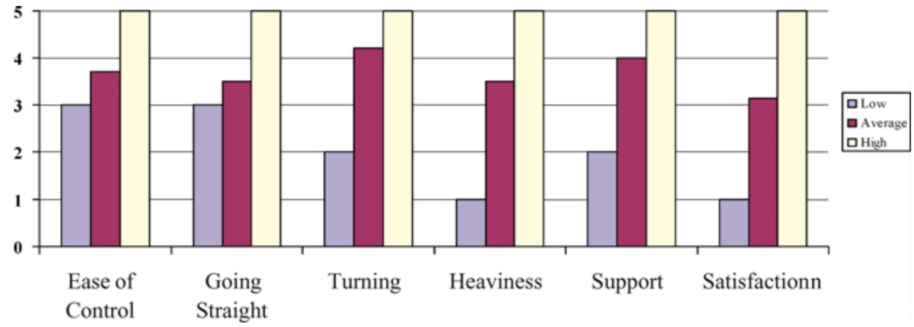

Figure 7. User evaluation on PAMM SmartWalker.

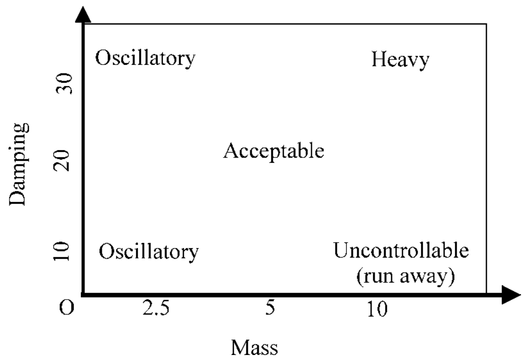

Figure 8. Admittance model effects.

they wanted to stop. When both mass and damping are too high, the system is too heavy. Similar tests were performed using the SmartWalker. There exists a range for both B and M that is acceptable; but the exact value for both PAMMs should to be tuned to each individual's needs.

It was also found that users have different requirements during different phases of motion. Elderly people feel less assured when they walk from a standstill with PAMM when M and B make PAMM feel light (or responsive) as they are afraid of falling. Therefore, the model should be less responsive at the start, with higher mass and damping. When an elderly wants to stop or slow down, PAMM should be able to stop immediately to avoid dragging the user forward. A model with bigger mass would require bigger damping to slow down. It might also need the user to apply backward force to slow down; causing oscillatory motion that is uncomfortable and dangerous for the user. That means it is necessary for the model to have higher damping and smaller mass when the user wants to stop.

Users always wanted PAMM to be light (meaning small driving forces) when they are walking at a certain speed. From the steady state response of the model, it is known that the force required to achieve a certain steady state velocity depends on the damping alone. Although it is necessary to let the user to feel some force so that she feels that she is in control, the force should be kept small to prevent the user from fatigue. That means the damping should be kept small.

Obviously, the fixed parameter model cannot satisfy the seemingly contradictory requirements for different phases of motion of the system. It can be seen that the damping has a more important role to play. An admittance model with velocity-dependent damping has been designed. The damping of the model is given by:

$$b = b_m - \frac{b_m - b_0}{V_m}|V| \tag{7}$$

where b_m is the maximum damping, b_0 is the minimum damping, V is the speed of PAMM, and V_m is the maximum speed allowed.

With the variable model, PAMM will initially respond to user input slowly due to the high mass and damping at low speed. However, when the user is walking steadily at a relatively high speed, the user will need less driving force due to the reduced damping and the speed will not fluctuate too much because of the high mass. When the user needs to stop, PAMM stops quickly as the damping increases, so that the user does not feel the drag. This model has been implemented on both the SmartCane and SmartWalker and was tested by more than 10 users.

Figure 9 shows force and speed profile of a user driving the SmartCane with the fixed damping model with a mass of 10 Kg and damping of 30 Ns/m. Figure 10 shows the force and speed of the same user with the variable model, with the damping in the range of 40 to 15 Ns/m. It is obvious that the user could walk with

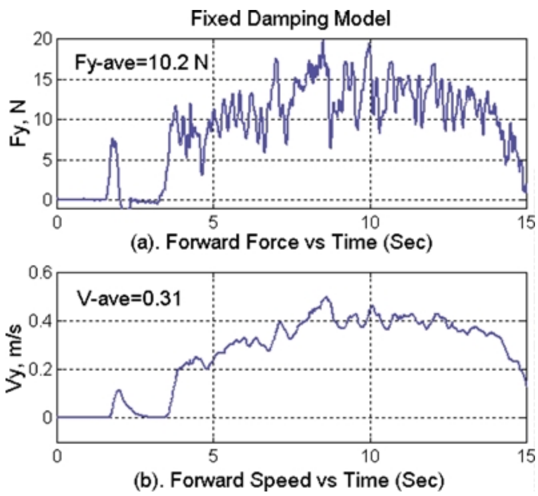

Figure 9. User force and speed profile with fixed damping model.

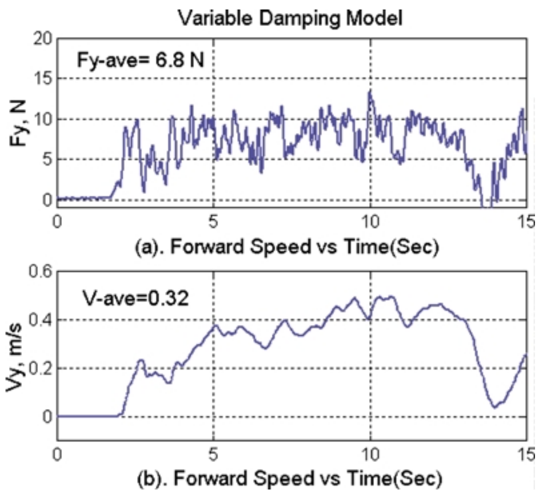

Figure 10. User force and speed profile with variable damping model.

less effort at the same speed. The users all agreed that the variable model is easier to drive.

4. Adaptive Shared Control

4.1. The Adaptive Shared Control Framework

The objective of the shared control design is to give the user as much control as possible while still ensuring adequate performance. For assistive devices like PAMM, the controller is used to assist the user rather than replace the user in performing his task. However, elderly users of PAMM could have limited physical and cognitive capability or irrational behavior. When the user demonstrates that he or she can not operate PAMM safely, more control should be given to the computer.

An adaptive shared control framework is proposed for PAMM, see Fig. 11. This approach has a similar structure of a classical adaptive controller (Narendra and Annaswamy, 1989). The system has a planner that generates an ideal path based on the task and its knowledge of the environment. PAMM determines its location in the environment by identifying the sign posts with a CCD camera (Dubowsky, 2000). The computer controller generates a virtual force input based on the preplanned and the actual trajectories. The user gives inputs to the system through a force/torque sensor. The two control inputs to the shared controller have an associated gain, K_{computer} and K_{human}, respectively. These gains reflect the control authority of the computer and the human. These gains are changed by the adaptation law. The adaptation law first computes a performance index J based on a metric δ, which is a measure of how well the user is performing. It then adjusts the two gains to minimize J. The output of the shared controller is fed to the admittance-based control, which in turn generates the low-level control commands for the physical system. The different parts of the algorithm are discussed in detail below.

The first step is to determine an ideal path and the velocity and acceleration profiles of the system along that path. The preplanned trajectory needs to take into account that the system has limited sensing capabilities and cannot know the entire environment explicitly. The main function of the computer controller is to guide the user back to the preplanned trajectory when the user deviates from it and when the shared controller deems it necessary based on the performance evaluation. However, one important issue is that the controller should not force the human to the trajectory and upset the balance of the elderly person. The computer limits the control forces based on the capability of the user. Another function of the computer controller is to act as a safety watchdog, even when there is no preplanned path. For example, when PAMM is under free driving by its user, the computer is also monitoring the user's speed, location, stability, and even health conditions. When there is an imminent danger, the computer should act by limiting the speed or guiding the user to a safe path.

The user's performance metric needs to include such factors such as proximity to obstacles, deviation from

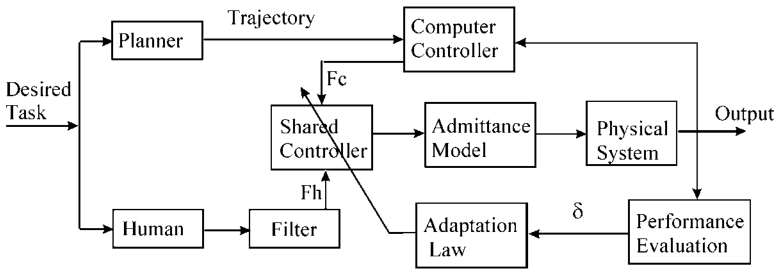

Figure 11. PAMM adaptive shared control system.

the trajectory, excessive or high frequency oscillation about a path, and tip over margins (Papadopoulos and Rey, 1996). The chosen metric here is a quadratic function combining all the factors considered and is given as:

$$\delta = k_1(x)^2 + k_2(\dot{x})^2 + k_3(\ddot{x})^2 + k_4(\mathrm{dis})^2 + k_5(\mathrm{S})^2 + \cdots \tag{9}$$

where

k_i = weighting factors
$x = \text{position}_{\text{ideal}} - \text{position}_{\text{actual}}$
$\dot{x} = \text{velocity}_{\text{ideal}} - \text{velocity}_{\text{actual}}$
$\ddot{x} = \text{acceleration}_{\text{ideal}} - \text{acceleration}_{\text{actual}}$
dis = distance to obstacles
$S = f(\text{stability criteria})$

The value of the weighting factors needs to be adjusted to some degree for a given population and environment.

The proposed adaptive shared control algorithm has the control law:

$$F = F_c K_{\text{computer}} + F_h K_{\text{human}} \tag{10}$$

where $K_{\text{computer}} + K_{\text{human}} = 1$.

The adaptation law adjusts the gain K_{computer}. First, at time t_i, a performance index $J(i)$ is calculated, which is an integral of the performance metric δ as follows:

$$J(i) = \sum_{k=1}^{i} \delta(k) e^{-\lambda(i-k)\Delta t} \tag{11}$$

where λ is the forgetting factor, δ is the performance metric, and Δt is the sampling time of the controller.

In this method, to avoid an abrupt change, the control authority is adjusted based on the demonstrated performance history of the user. However, past data should carry less weight on the adaptation, thus an exponential forgetting factor λ is introduced. The parameter λ has units of $1/s$. With a smaller λ (or longer forgetting term), the control authority is changed more gradually.

With the performance index $J(i)$, the gain for the computer control is calculated using the following adaptation law:

$$K_{\text{computer}}(i) = 1 - e^{-\beta J(i)} \tag{12}$$

where β is the gain used together with λ to adjust the behavior of the adaptation.

Under this adaptation law, the controller gains, K_{computer} and K_{human}, are adapted to the user's capability measured by the performance metric. These gains determine the balance of the control authority that the human has compared to the preplanned trajectory, or how responsive the system will be to the user. Depending on the relative control allocation, a system can be said to be in manual, shared, or autonomous control mode. However, due to the high sampling frequency these modes are essentially continuous rather than discrete, and the adjustment of control authority is automatic.

4.2. *Field Experiments of the Adaptive Shared Control*

It is difficult to model the interactive behavior of a human user operating the PAMM system and thus the validation of the shared control design depends largely on experimental work with real users. The field trials for the adaptive shared control were conducted at an eldercare facility. In general, users of the SmartCane have better navigation skills than walker users. Thus, these trials were tested using the SmartWalker.

The tests were conducted in the users' residence. The test path has a total length of 35 meters that runs from

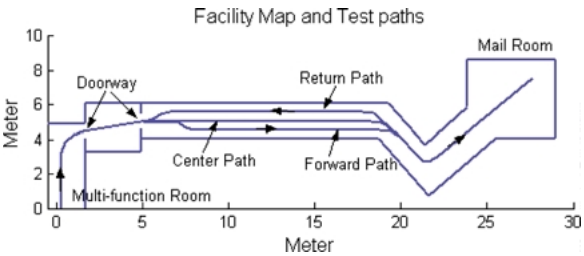

Figure 12. Test path design.

Figure 13. Elderly users (94 and 85 years old) testing PAMM SmartWalker.

a multifunction room, passing through two standard doorways that are 3 feet wide, running the long corridor that is 6.5 feet wide, to a mail room at the reception area, see Fig. 12. In the corridor, three different paths were selected, the one along the center is designed to make the task easier, the other two close to the wall are designed to make the task tougher as the user has to walk to the right and not hit the wall. These paths were not marked on the floor during the tests.

A group of 5 female and 1 male residents participated in the experiments. Figure 13 shows a 94 year old female user and a 85 year old male user testing the PAMM SmartWalker. The age of these residents ranges from 84 to 95 and they all need walkers for their activities. Each user tested the SmartWalker under three different control modes: free driving, full computer control, and adaptive shared control. Different forgetting factors were also tested to show its effects on the control performance. Before the test with the adaptive shared control, each user was asked to drive PAMM freely along the path for three to five times. These tests were intended to get the user familiar with PAMM and to get all users the same exposure to PAMM.

Each user then tested PAMM under free driving, adaptive shared control, and full computer control along the path. The order of the control modes tested with each user was different in order to counterbalance the effects of learning. The users were not told which control mode they were using. The performance metrics used in these tests are the deviation from the path and the distance to the wall, which is expressed as:

$$\delta = k_1 * dev^2 + k_2 * \frac{1}{dis^2} \tag{13}$$

Figure 14 shows a typical user trajectory and the change of the computer control gain under the adaptive shared control. It clearly shows that when the use passes the doorway, the performance index value is

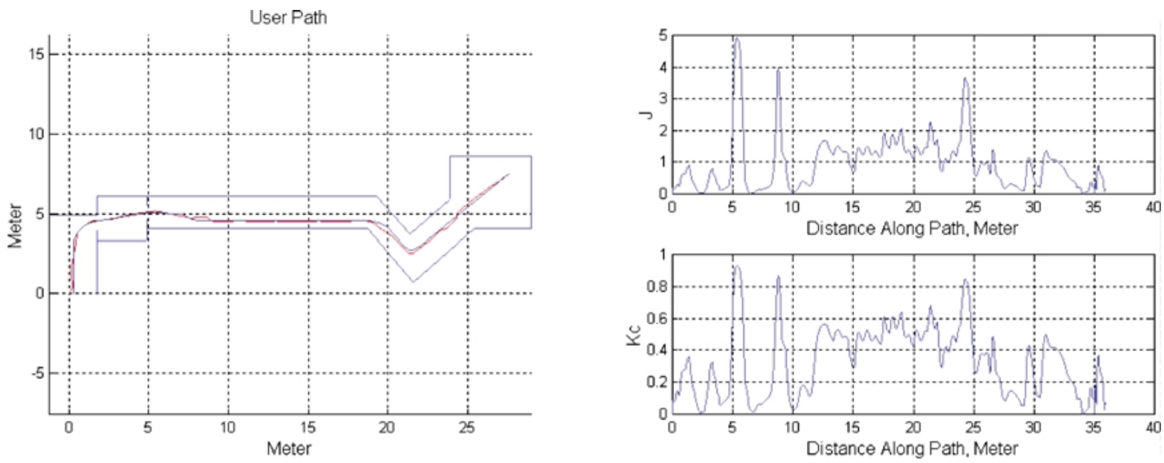

Figure 14. Adaptive shared control gain change.

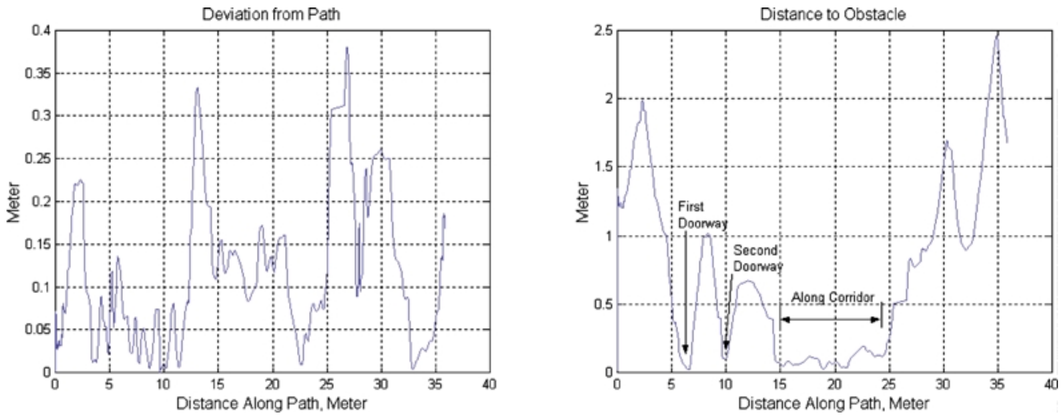

Figure 15. Free driving performance.

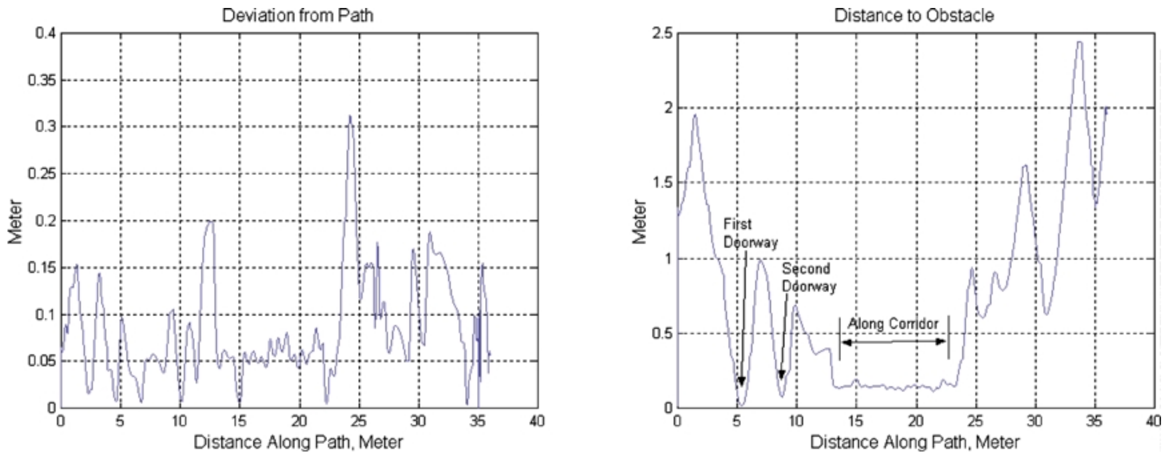

Figure 16. Adaptive shared control performance.

high and the computer control gain increases. In other parts of the trajectory, the computer control gain decreases as long as the user is not getting too close to the wall.

To compare the performance of the user under different control modes, the distances to the walls and deviations from the path of a user under the three tests were plotted in Figs. 15–17 respectively. Figure 15 shows that, under free control, the user deviated from the path as much as 0.35 meters. The user frequently got very close to the wall along the corridor. Under the adaptive shared control, the deviation is smaller and the user could stay on the path and maintain a safe distance from the wall along the corridor. Although the performance was improved, the user could not notice the difference from the free driving. It can be seen that performance under the full computer control is also good. However, most of the users did not like the full computer control and complained that "PAMM has a mind of its own." This is because the controller does not allow the user to deviate from the path even when she is far from the wall.

Figures 18 and 19 show the effects of forgetting factor. With short forgetting terms (bigger λ value), the computer control gain changes quickly. The controller behaves like a reactive obstacle avoidance algorithm. With longer forgetting terms, the control is not returned to the user immediately after the computer gains more control; therefore, the performance is better. The value of the forgetting factor should be different for each user. Longer forgetting factors can be used for users with less capability.

These experiments demonstrated the effectiveness of the adaptive shared control. The adaptive shared control

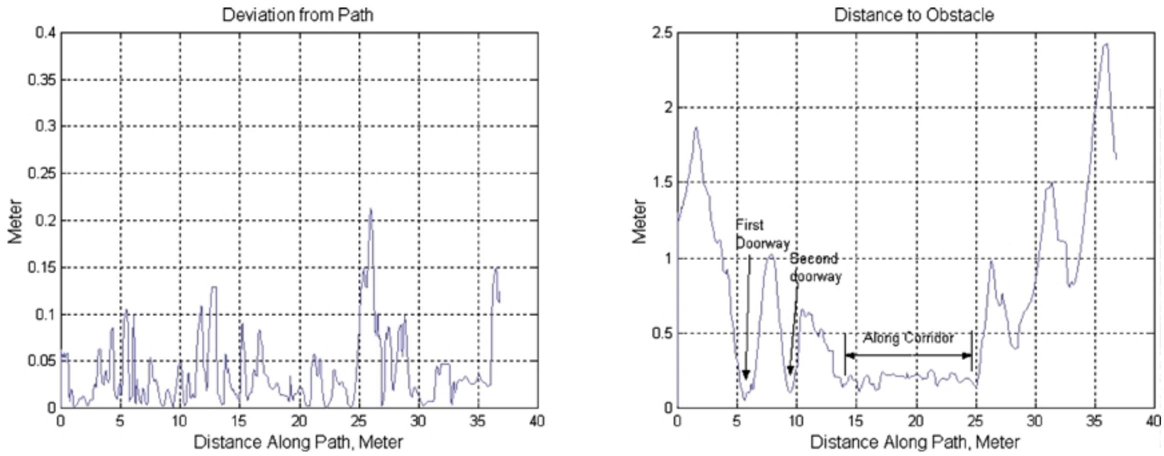

Figure 17. Full computer control performance.

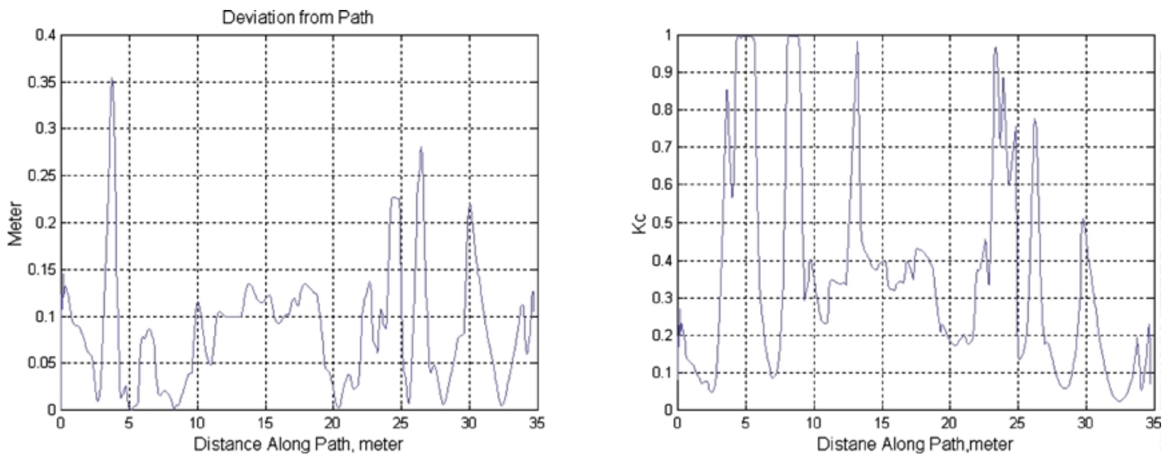

Figure 18. User performance with shorter forgetting term ($\lambda = 10$).

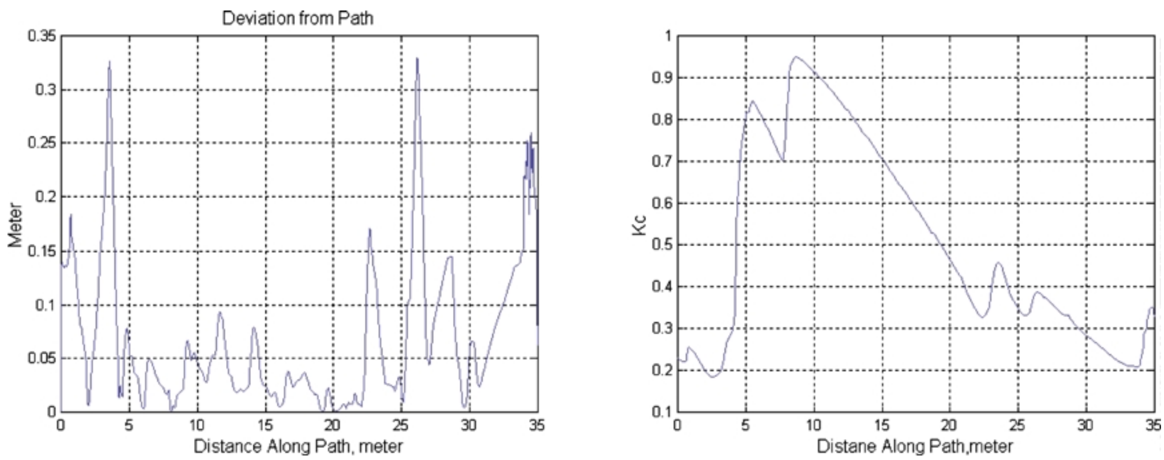

Figure 19. User performance with longer forgetting term ($\lambda = 0.1$).

helps improve the performance of the user. In practical applications the control modes are continuous rather than discrete, and the switching of control is based the user's performance.

5. Summary and Conclusions

Aging of the population coupled with escalating cost of healthcare makes it important to develop robotic assistive devices for eldercare. A personal mobility aid and health monitoring (PAMM) system has been developed to assist the elderly living in private homes or assisted living facilities. The control system development of PAMM was presented in this paper. The objective of the PAMM control system is to enable users and PAMM to work interactive and cooperatively. The two most important aspects of this design are the human machine interaction control and the adaptive shared control.

With the force/torque sensor as the main human machine interface, an admittance-based human machine interaction control has been developed. The admittance control allows the user to have a natural and intuitive control of PAMM. The control can be tuned to individual characteristics by changing the model defined in software. Through extensive field experiments with various parameters of the model, the effects the model parameters have been identified. Based on the experimental study, an adaptive admittance model with velocity-dependent damping has also been tested and it demonstrated smoother motion and increased user comfort. In addition, an adaptive shared control framework has been developed to allocate control authority between PAMM and its user. The control allocation is based on the demonstrated performance of the user. The control design has also been validated in the field trials at an assisted living facility.

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