Robotic Personal Aids for Mobility and Monitoring for the Elderly

Matthew Spenko, Haoyong Yu, and Steven Dubowsky

***Abstract*—Two rehabilitation devices, or personal aids for mobility and monitoring (PAMM), for use by the elderly are presented. The devices are intended to delay the transition from eldercare (assisted living) facilities to nursing homes. The robotic PAMMs provide support, guidance, and health monitoring. Two experimental systems are described: a cane and a walker. Issues of mobility, sensing, and control, as well as experimental data from trials in an assisted living facility using both systems are presented.**

***Index Terms*—Elderly, mobility, personal aids for mobility and monitoring (PAMM), SmartWalker, SmartCane.**

I. Introduction

According to the U.S. Department of Health and Human Services, America's elderly population is growing rapidly. In the 2000 U.S. census, persons 65 years or older numbered 35 million and represented 12.4% of the U.S. population [2]. As some people age, their degrading physical and cognitive conditions require them to move into eldercare facilities and nursing homes.

Eldercare (assisted living) facilities typically provide services such as bathing and meal preparation. They do not provide labor-intensive support required by elderly with poor physical and mental conditions. This lack of support can be especially difficult for residents suffering from senile dementia, a disorder that affects 30%–40% of assisted living facility residents [1]. A personal assistant is often necessary for residents who require physical assistance, guidance when walking, medication regulation, and health monitoring and scheduling (see Table I). When this occurs, residents often must move into a nursing home, which is equipped to provide more care than an assisted living facility. However, in nursing homes the quality of life is often lower and the costs are substantially higher than assisted living facilities. For example, a nursing home can cost from \$90 000 to \$100 000 per year compared to \$40 000 per year for an eldercare facility [4]. The economic benefits are obvious for postponing the move into a nursing home.

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TABLE I
COMMON PHYSICAL AND COGNITIVE NEEDS OF THE ELDERLY

Needs	Deficiencies	Causes
Guidance	Failing memory, disorientation	Senile dementia, Alzheimer's
Physical Support	Muscular-skeletal frailty, instability	Osteoporosis, Parkinson's, Arthritis, etc.
Health Monitoring	Cardiovascular system, potential strokes and heart attacks	Age, lack of exercise, illness
Medicine and Other Scheduling	Need for a variety of medicines coupled with a poor memory	Senile dementia, general frailty

This paper presents two robotic systems, the SmartCane and the SmartWalker, which comprise a group of devices termed PAMM (personal aids for mobility and monitoring). PAMMs are designed to extend the stay of the elderly in assisted living facilities. Although PAMM systems were originally designed for this purpose, their features enable them to be used as rehabilitation devices for younger patients. This paper provides an overview of the PAMM program and addresses issues such as mobility, sensing, control, and health monitoring.

The PAMM concept is shown in Fig. 1. An individual uses the PAMM system for support and guidance. The PAMM is capable of detecting and maneuvering away from obstacles. The PAMM uses an upward looking camera for localization and also can communicate with a central computer. The central computer provides PAMM with a map of the facility including the location of stairs and any permanent obstacles, a profile of the user, and any instructions such as a limitation to the user's speed. In turn, PAMM provides the central computer with the user's location, health status, and requests. The user inputs instructions to PAMM by applying forces to a force/torque sensor and via voice commands. The PAMM contains sensors that enable it to continuously monitor key vital signs of the user.

A shared adaptive controller monitors the user's performance and mediates between the computer instructions and the user's intent by giving the user as much control as he can safely handle. The basic idea is to have the computer provide assistance only when the user needs it.

II. Background

There has been substantial interest in the area of robotic aids for the elderly and disabled. The Pam-Aid was developed at the University of Dublin for physical support and obstacle avoidance for frail blind people [11], [12]. The Hitomi was created to aid the blind in outdoor environments [14]. The robot provided

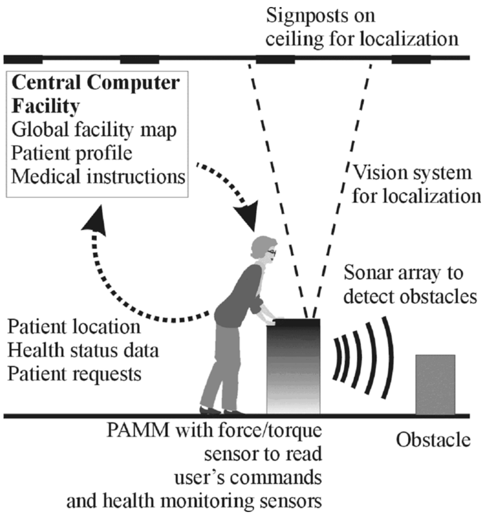

Fig. 1. PAMM system concept.

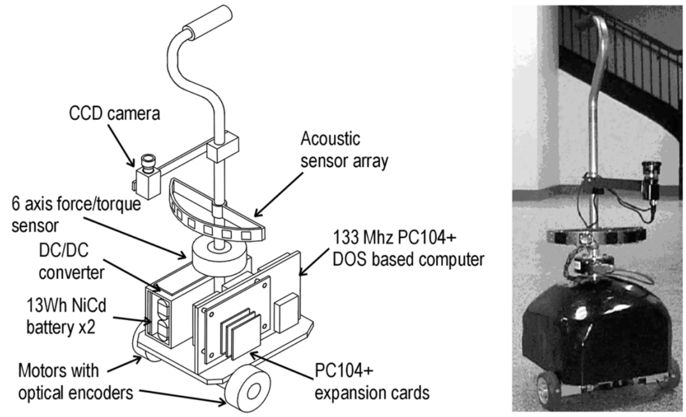

Fig. 2. SmartCane.

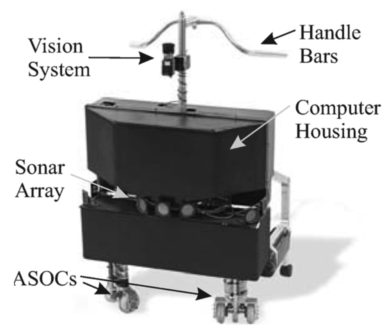

Fig. 3. SmartWalker.

the user with orientation and map-based guidance based on obstacle and landmark information.

Two additional aids for the elderly are the Care-O-Bot and NurseBot. The Care-O-Bot is used as a mobility aid, to perform household jobs, and for communication and entertainment [9]. The NurseBot was developed to study human–machine interface methods, speech interface, and face tracking [3]. The most current version, named Pearl, also has the ability to guide elderly users around an assisted living facility [13].

Hitachi developed the Power-Assisted Walking Support System [16]. The device supports users when getting out of bed, walking, and sitting down. The device is used mostly for rehabilitation in a large well-known setting. It is impractical in an eldercare facility setting due to its large size and lack of maneuverability in a crowded environment. An unpowered walker was created at the University of Virginia [21]. Much of the work focused on navigating the walker based on the inferred intent of the user [22].

Although the above research has yielded important results, challenges of meeting the needs of the elderly remain. The large size and nonholonomic constraints of the above systems pose important maneuverability limitations. Questions remain about the nature of control between the assistive device and a human user who might have diminished physical and cognitive capabilities. These problems are addressed by the PAMM project.

III. Physical System Description

Two implementations of the PAMM concept have been developed. The first is a cane configuration called the SmartCane (see Fig. 2), and the second is the SmartWalker [6], [18]. All of the SmartCane's components, as well as the SmartWalker's, are based on commercial technology to keep the system cost within reasonable bounds. Target retail costs are approximately $2500 for the SmartCane and $5000 for the SmartWalker. These figures were based on discussions with healthcare professionals.

The SmartCane uses a six-axis force/torque sensor to measure the forces and torques that the user applies to the handle. This input is translated by an admittance control system implemented on a PC104 computer to provide velocity and direction commands to the SmartCane's skid steering drive mechanism. This allows each drive wheel to operate independently. Thus, when the user pushes the cane forward, the cane responds by driving itself forward. Twisting the handle causes the cane to rotate. The admittance control system allows the SmartCane to be programmed to have a different "feel" for each user and unique situation. For example, when the user is just starting to move forward, the SmartCane can be made to feel slow and stable. When the user is walking fast and needs less support, the SmartCane can be made to feel lighter and more responsive. The sensors of the SmartCane include a charge-coupled device (CCD) camera for localization and a sonar array for obstacle detection.

To meet the needs of users who require the support of a walker, the SmartWalker was developed (see Fig. 3). In a typical assisted living facility, the residents are roughly equally divided among those who require a cane, a walker, or no mobility assistance.

The SmartWalker uses several of the same features as the SmartCane, such as the force/torque sensor, localization camera, sonar array, and PC104 computer. The SmartWalker augments these features with a longer battery life, added physical support, health monitoring capabilities, and most importantly omnidirectional movement. It provides the SmartWalker with the ability to continuously move from any position and orientation to any other. The walker requires an omnidirectional drive system because it is larger and bulkier than the cane. Although appropriate for the small footprint of the SmartCane, a skid-steer drive would restrict the SmartWalker's mobility due to its nonholonomic nature (see Fig. 4).

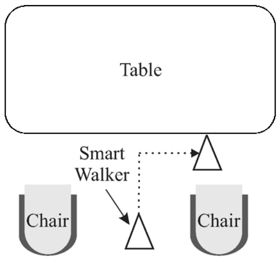

Fig. 4. Omnidirectional movement.

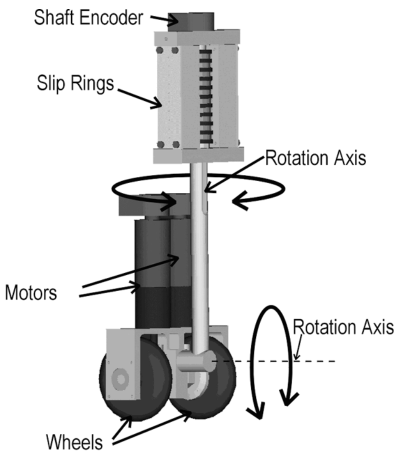

Fig. 5. ASOC.

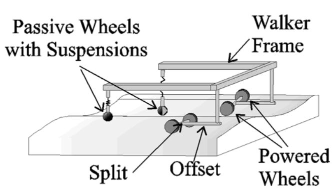

Fig. 6. Omnidirectional platform diagram.

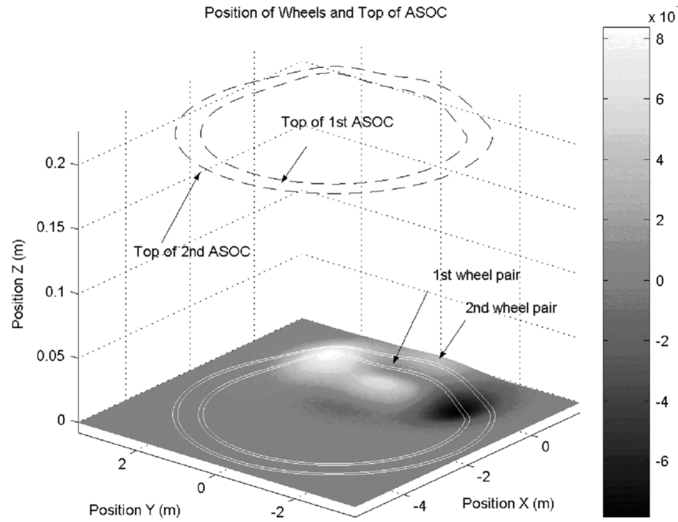

Fig. 7. Simulation results of the SmartWalker traversing an uneven floor.

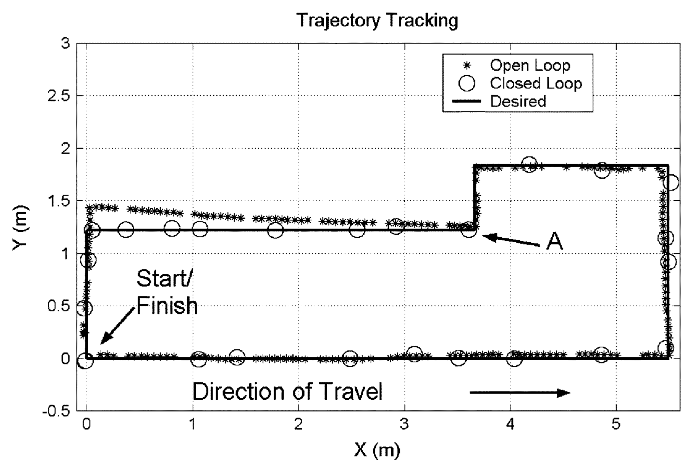

Fig. 8. Trajectory following of the SmartWalker using both open-loop and closed-loop control.

For use in an eldercare facility, an omnidirectional drive system must be able to accommodate nonideal floors (floors that might have dirt, debris, or small obstacles) that might be carpeted or uneven. It must also be power efficient. The SmartWalker uses a novel, power-efficient, omnidirectional drive system that has been shown to be capable of effective operation on a nonideal floor, such as would be found in an eldercare facility. The omnidirectional drive system is based on an active split offset castor (ASOC) (see Fig. 5, [19], [24]).

Two ASOCs connected by a rigid link along with two passive castors make up the SmartWalker's mobility platform (see Fig. 6).

The platform's performance on nonideal floors was evaluated by simulations and experiments. The simulations showed that bumps in the floor caused the ASOC to deviate from the intended path by approximately the height of the bumps. A typical eldercare facility floor might have bumps in the range of 0–3 mm with a possible maximum height of 10 mm. Further simulations showed that the SmartWalker traversing a 14-m path over an uneven floor returns to within 4 mm of its starting position (see Fig. 7). This is difficult to see in the figure, but it also indicates that the design is well suited for use on uneven floors.

Experimental results also show the SmartWalker's ability to maintain a path. Fig. 8 shows the results of the SmartWalker traversing a 15-m path. The asterisks indicate the walker's path without feedback information about its location so that its trajectory is based on open loop dead reckoning. At point A, the walker encounters a particularly rough section of the floor and moves slightly off path. Even so, it returns to within 0.3 m of its starting position. The circles indicate the walker's path using a closed loop system that uses ceiling markers for localization. The closed loop system returns to within 0.1 m of its desired location, which is the error of the localization system. Such results show that the tracking error introduced by the uneven floors fall within the abilities of the control system to correct.

The SmartWalker's omnidirectional capabilities are demonstrated here as experimental results. Fig. 9 shows the results of the center of the SmartWalker moving in a straight line in the Y direction while its body rotates in a counterclockwise direction.

A previous omnidirectional concept that is able to tolerate uneven floors as well as dirt and debris is based on the active offset castor (see Fig. 10, [20]). However, the ASOC has better power consumption than the active offset castor [23]. The power

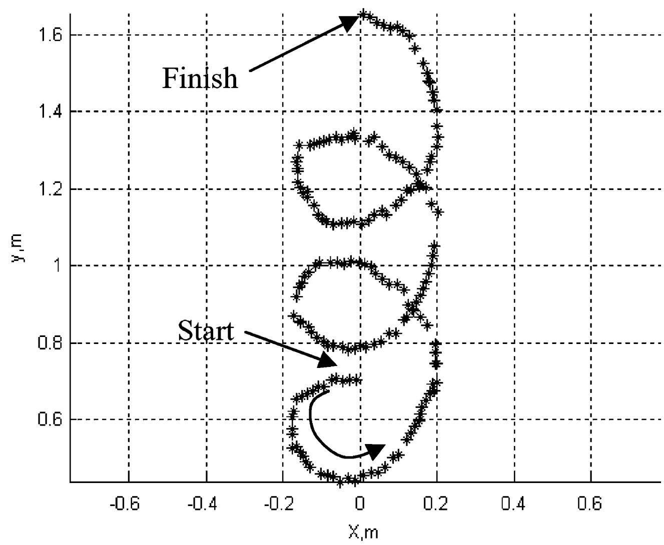

Fig. 9. SmartWalker demonstrating omnidirectional movement.

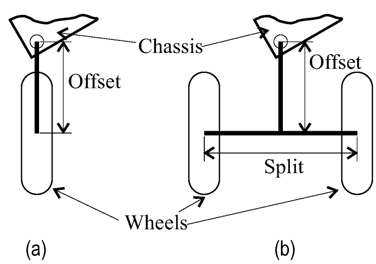

Fig. 10. Active offset castor and ASOC. (a) Conventional active castor. (b) ASOC.

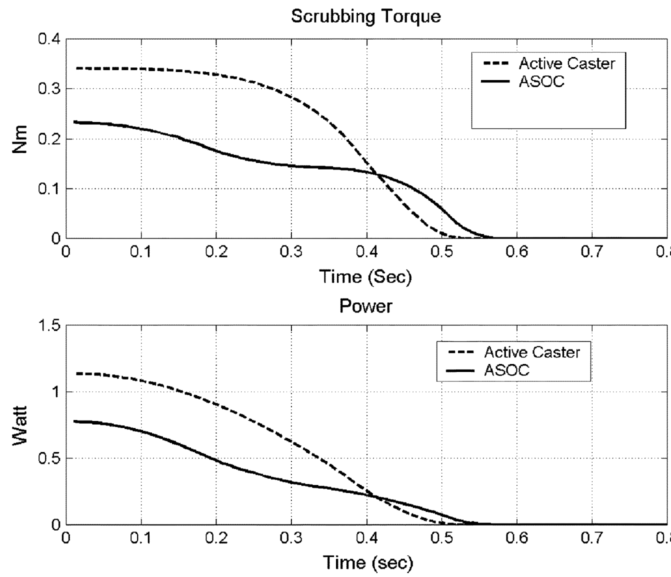

Fig. 11. Scrubbing torque (torque required to twist a wheel about its vertical axis) and power consumption for an ASOC and an active castor.

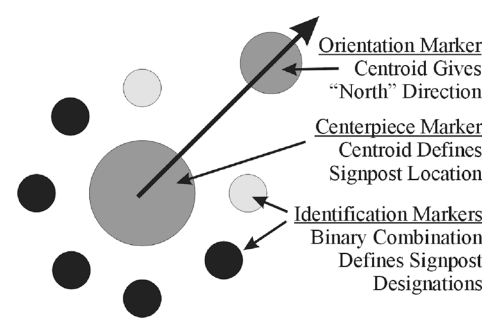

Fig. 12. Signposts used for localization by the PAMM systems.

consumption of an assistive walking device such as the SmartWalker is important since it is battery powered. Tests and analysis show that the SmartWalker could meet the needs of an elderly person for a typical day in an assisted living facility while being recharged only during an eight hour night. For example, the power consumption of an active offset castor is compared to an ASOC when both are commanded to move to the right (see Fig. 11, [23]).

The uniqueness of the SmartWalker's omnidirectional platform makes it well suited for an eldercare facility. The platform's use of conventional wheels cause it to be robust to floor irregularities while its active split offset design allow it to be power efficient, which is key to maintaining battery life. In addition, the omnidirectional capabilities make the SmartWalker extremely maneuverable in all situations.

IV. Sensors

The PAMM systems use three main sensors for control and navigation: a sonar array for obstacle avoidance, a force/torque sensor for reading the user's input, and a camera for localization. The sonar array is used for identification and localization of objects not given on the facility map. Sonar was chosen because it is lightweight, has a small volume, and is low cost. The six axis force/torque sensor reads the user inputted forces and torques applied to the handle of the PAMMs. The force and torque components are used for health monitoring and driving as discussed in Sections V and VI, respectively.

A typical assisted living facility has one to five floors with approximately 7500 ft^2 (710 m^2) per floor [6]. The large size coupled with large numbers of similar rooms makes recognition by vision and acoustic systems difficult and computationally complex. To avoid these problems, PAMMs localize themselves by using a camera that looks at passive signposts placed on the ceiling (see Fig. 12).

The signposts have three elements: orientation marker, centerpiece marker, and identification markers. The orientation markers of all of the signposts in the building are aligned. The centerpiece marker defines the signpost location. The identification markers are either black or white and represent a binary sequence so each signpost can be individually recognized. A design with N placeholders for identification markers allows $2(N+1)-1$ separate signposts. For example, if the camera's field-of-view on the ceiling is 12 m^2, then a 3500 m^2 facility would need approximately 300 signposts, and a design with $N=8$ would suffice. Experiments show that the system is able to localize itself to within 10 cm.

The sensors on the PAMM systems are simple and inexpensive, but highly effective at localization, obstacle detection, and reading the user's inputs.

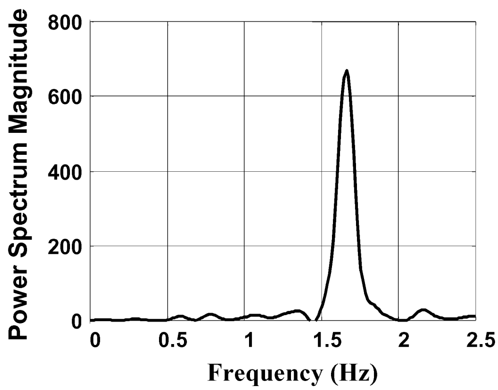

Fig. 13. Filtered frequency spectrum of a normal adult gait (from a researcher).

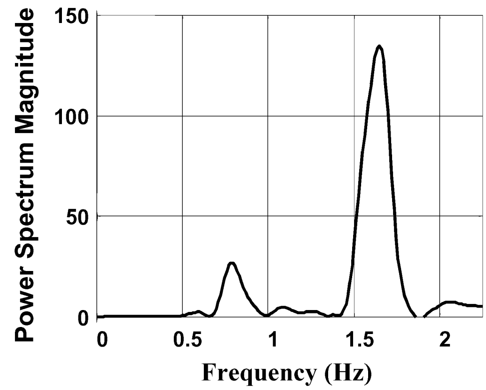

Fig. 14. Filtered frequency spectrum a stroke patient's gait (from an elderly subject).

V. Health Monitoring

The PAMM's continuous health monitoring sensors are effective because they can detect short term changes as well as long term health trends. The PAMMs can record the user's activity level (speed and applied forces), which over time can help physicians better monitor the user's health [5].

A robust noninvasive ECG-based pulse monitor was developed for the SmartWalker. An ECG-based monitor was used because of its high tolerance to mobility disturbances. This monitor was tested rigorously and performed well in conditions similar to those found in an eldercare facility [5].

Experiments were also performed utilizing the force/torque sensor of the PAMM systems along with odometry information to study the user's gait. Recording the stride-to-stride variability in gait over a period of time has been proposed as effective predictors of falls [10]. Experiments were performed with six individuals from an eldercare facility. The users were asked to walk with an early prototype of the SmartWalker in a straight line for approximately 10 m.

A power spectrum was calculated from PAMM's velocity to resolve the user's stride length and frequency. The peaks in the power system represent the stride frequency, and the shape of the power spectrum is a function of the gait symmetry. A symmetric gait has all of the energy located at twice the stride frequency (see Fig. 13). However, an asymmetric gait has energy located at the stride frequency as well as at higher frequencies (see Fig. 14). An asymmetric gait could be an indicator of such events as a physical injury or a minor stroke. While the work done with the PAMM in this area is not sufficiently detailed to be medically conclusive, it does suggest that the PAMM can provide significant information about the gait characteristics of a user.

VI. User Control Interface

Both PAMM systems use a six-axis force/torque sensor attached to the PAMM's handle as the main user control input interface (see Fig. 15). The force/torque sensor signals are interpreted for motion control by using an admittance controller [7] (see Fig. 16). The signals generated by the force/torque sensor contain the user's intention as well as support and stability information about the user.

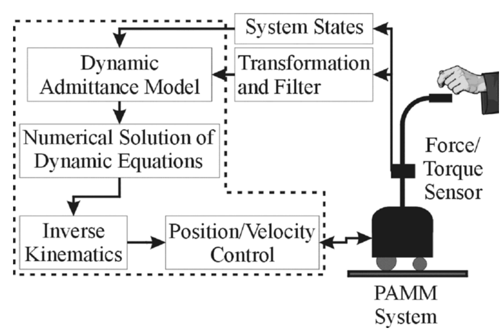

Fig. 15. User control system diagram.

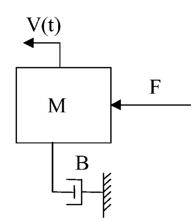

Fig. 16. Dynamic model used for admittance control.

The admittance model can be tuned for each individual user. This means that the PAMM system can be made to feel maneuverable and light for an agile person or slow and stable for someone who needs more support. The admittance of the modeled dynamic system is defined as the transfer function from the user's forces and torques $\mathbf{F}(s)$ to the PAMM's velocities $\mathbf{V}(s)$. It is expressed as

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

The response of the PAMM is obtained by first solving the dynamic equations in real time and then solving the inverse kinematics of the physical system to get the desired actuator velocity. The design challenge is to properly determine the appropriate dynamic model to give the user a comfortable feeling. This is done by choosing a metric to evaluate the performance of the model so that the operator effort is minimized. Field trials were performed to address these questions.

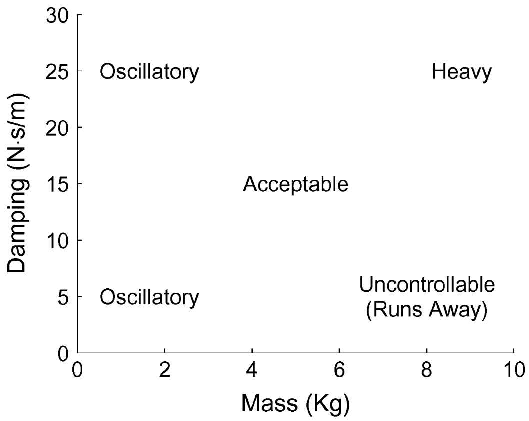

Fig. 17. Effects of various mass and damping coefficients of the admittance model.

The first tests were conducted to evaluate the general usability of a PAMM system with admittance control. It was found that the user exerted support force was in the range of 40–70 N. This closely matched the support force measured on a conventional walker with two wheels in the front and skids in the rear [8]. This, along with a questionnaire survey of the users, indicated that the users were comfortable relying on the PAMM for support [23].

To study the acceptance of PAMM and to help select the values of the admittance model, questionnaire surveys were used in the field experiments as a qualitative measure. Several elderly were asked to drive the two PAMM systems freely at the facility and compare them to their conventional mobility aids. Questions were asked to evaluate the ease of control, driving effort, ease of learning, physical support, and overall acceptance of PAMM as a mobility aid. The results of the evaluation are presented in [8], [25].

Nine models with different mass and damping combinations were tested with the SmartCane. M was set to 2.5, 5, or 10 kg and B was set to 10, 20, or 30 Ns/m. Fig. 17 shows the effects of the different combinations of B and M on the performance and feel of the SmartCane. However since the "feel" of the PAMM systems can be tuned, both the SmartWalker and the SmartCane can exhibit similar behavior. It was observed that the same values for B and M were appropriate for both PAMM systems.

In general, a small mass and damping resulted in an oscillatory motion. A small mass and large damping produced an oscillatory motion due to high frequency noise. Large mass and small damping made the effective inertia too large which resulted in the users being dragged along by PAMM. The combination of high mass and high damping parameters yielded a slow and sluggish system. It was found that there exists a suitable range for both B and M for each user that meets his individual needs.

In addition to selecting different parameters for each individual, it was found that the users preferred that the parameters change for different phases of the user's motion. They want PAMM to feel slow and steady at the beginning and end of their motion, while feeling light and responsive when they are moving faster. Requiring large user inputted forces at higher speeds was found to be fatiguing by the elderly users. Instead,

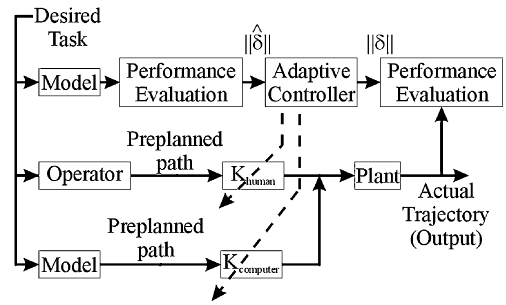

Fig. 18. Adaptive shared control framework.

to achieve this performance a variable damping model was developed and is given by

$$b = b_m - \frac{b_m - b_0}{V_m}|V| \tag{2}$$

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. This model has been implemented on both the SmartCane and SmartWalker and was tested by more than twenty users. They generally agreed that the variable model is more stable and less fatiguing than the constant parameter model [25].

VII. Adaptive Shared Control

A shared adaptive control algorithm was developed to share the control of the PAMM systems between the computer and the user. A PAMM system is capable of completely autonomous navigation through the eldercare facility. It also can be completely controlled by the user. The question that was addressed was how to control the system in such a way to give as much control as possible to the user in spite of possible degraded cognitive function while keeping the user safe. For example, when the user is acting safely and effectively, he should have complete control of the PAMM. However, the computer should have more control authority when the user's performance begins to demonstrate that he can not operate a PAMM safely.

An adaptive shared control framework is used for the PAMMs (see Fig. 18, [25]). This framework has a similar structure to that of a classical adaptive controller [15].

The path planner generates a path based on its knowledge of the environment and a task such as going to the facility's nurse's office. If the user deviates from the preplanned path, and the shared controller deems it necessary based on the performance metrics, the computer controller will gently guide the user back. It is important that the controller never force the human to an unwanted trajectory, which could result in the user losing his balance.

The computer controller generates a virtual force input based on the computer generated and actual paths. The two control inputs have respective gains associated with them, $\mathrm{K}_{\mathrm{computer}}$ and $\mathrm{K}_{\mathrm{human}}$, where these gains reflect the control authority of the computer and the human, and the following relationship holds:

$$\mathrm{K}_{\mathrm{computer}} + \mathrm{K}_{\mathrm{human}} = 1. \tag{3}$$

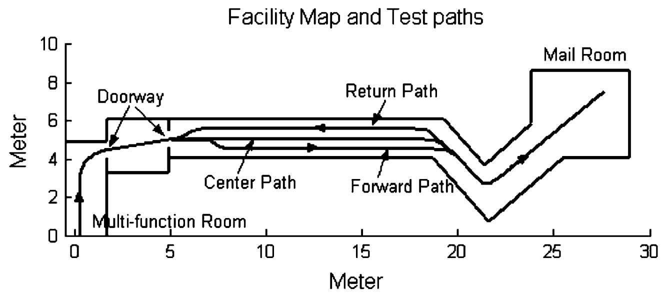

Fig. 19. Field trial path.

Fig. 20. Ninety-four-year-old PAMM user.

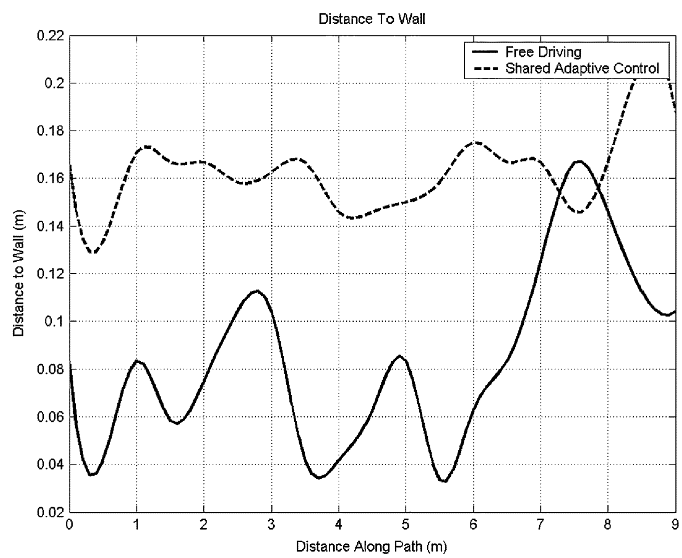

Fig. 21. Distance to wall for free driving and shared adaptive control for a single subject.

The two gains are changed by the adaptation law, which first computes a performance index J based on a metric δ. The metric is a measure of the user's performance. The adaptation law 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 performance metric includes proximity to obstacles, deviation from the path, excessive or high-frequency oscillation about the path, and tip over margins [17]. The metric chosen here is a quadratic function that considers the above items

$$\begin{aligned} \delta &= k_1(x)^2 + k_2(\dot{x})^2 + k_3(\ddot{x})^2 \\ &\quad + k_4(\mathrm{dis})^2 + k_5(S)^2 + \cdots \\ \text{where } k_i &= \text{weighting factors} \\ x &= \text{position}_{\text{ideal}} - \text{position}_{\text{actual}} \\ \dot{x} &= \text{velocity}_{\text{ideal}} - \text{velocity}_{\text{actual}} \\ \ddot{x} &= \text{acceleration}_{\text{ideal}} - \text{acceleration}_{\text{actual}} \\ \mathrm{dis} &= \text{distance to obstacles} \\ S &= f(\text{stability criteria}). \end{aligned} \tag{4}$$

The adaptive shared control algorithm is given as

$$F = F_c \mathrm{K}_{\text{computer}} + F_h \mathrm{K}_{\text{human}} \tag{5}$$

Since it is challenging to model the interaction of the human user with the PAMM systems, validation of the adaptive shared control largely depends on experimental work. Field experiments were performed at an eldercare facility to study the adaptive shared control algorithm.

A representative result is shown in Fig. 19. A 35-m test path ran from a multifunction room through two standard 0.9-m wide doorways, along a 2-m-wide corridor, and finished in a reception area.

Three paths were selected: one in the middle of the corridor and two along the sides of the corridor to make the task more difficult. Note that the paths were not marked on the floor. Five females and one male participated in this experiment (see Fig. 20). Their ages ranged between 85 and 95 years old. The users were asked to drive the SmartWalker freely to get acclimated to the system before the experiment began.

Each user tested three different modes in a random order: free driving, full computer control, and adaptive shared control. A comparison of the performance of the user walking along the corridor under free driving and the shared adaptive control is shown in Fig. 21. It shows that the user more easily maintained a safe distance from the wall under shared adaptive control than with free driving. Although the performance was improved, the user could not notice the difference between the two. The 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 he is far from the wall.

VIII. Conclusion

Both the SmartCane and the SmartWalker were designed to delay the transition of an elderly individual from an assisted living facility to a nursing home. Both systems use an adaptive shared control architecture as well as an admittance based control strategy. The two PAMM systems use a camera coupled with signposts on the ceiling for localization and a sonar array for obstacle detection. In addition, the SmartWalker uses a novel omnidirectional platform that is well suited to an eldercare facility as well as incorporating health monitoring sensors. The systems have been experimentally tested in an eldercare facility and have been shown to perform well and have high user acceptance.

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