PAM-AID - A Study in Human-Machine Cooperative Behaviour

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Abstract

The research described in this thesis attempts to address the needs of a growing number of people with both a visual impairment and a mobility impairment. These people tend to live a very inactive lifestyle, often confined to bed because of lack of care-givers to assist them. A sedentary lifestyle can lead to accelerated aging and make people more susceptible to disease and injury which generally results in a severe reduction in the quality of life. This thesis proposes a novel mobile robot concept which gives frail, visually impaired people increased autonomy. The robot provides both the necessary physical support along with essential navigation assistance to promote *independent* mobility. The device was initially designed for an indoor environment such as an assisted living facility, nursing home or hospital. Detailed user requirement studies were carried out in Ireland and Sweden. Development was interleaved with frequent evaluations by real users. This ensured that user requirements were driving the design process from inception to completion.

The robot is mechanically passive. It is the user who provides the propulsive force while the robot provides the guidance through active steering based on its world model. The system thus provides a very interesting testbed for studies in human-machine cooperative behaviour and user interface design. The navigation system is composed of two components, a general obstacle avoidance (GOA) routine and a manoeuvre planner. The manoeuvre planner is required for fine motion planning in order to escape from cluttered spaces upon failure of the GOA. A trajectory execution module endeavors to realise manoeuvres generated by the planner. A dynamic model of the human-machine system helps to ensure that the planned path is successfully followed. The manoeuvre planner was found to be especially useful to users with no residual vision. It drastically reduced the number of collisions and the efficiency with which users navigated in environments with relatively high obstacle density and many dead-ends.

While the PAM-AID system was developed primarily as a mobility aid with navigation capability, it is also a potentially valuable platform for the continuous monitoring of certain physical characteristics of the user such as gait. Variability in gait parameters can be indicative of certain conditions such as a susceptibility to falls. It is shown through both time-series analysis and frequency analysis of sensor data that stride length can be accurately measured and gait asymmetry can be detected. This monitoring is non-evasive and can be conducted on a long-term basis.

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Chapter 1

Thesis Overview

1.1 Introduction

This thesis describes the development of a robotic mobility aid to address the needs of frail, visually impaired people. Aside from necessary physical support associated with more traditional walkers, the robot provides navigation assistance such that users can move more independently in an environment such as an assisted living facility or nursing home. The visually impaired community is comprised predominantly of elderly people. Over 75% of people registered as having a visual impairment are over the age of 65 [34]. Where frailty is not an issue, a long cane or guide dog can be used for navigation assistance. A frail visually impaired person who requires the support of a zimmerframe for mobility cannot simultaneously manipulate a long cane. Currently, these people require assistance from care-givers who are generally under severe time pressures and cannot give individuals the attention which they require. This

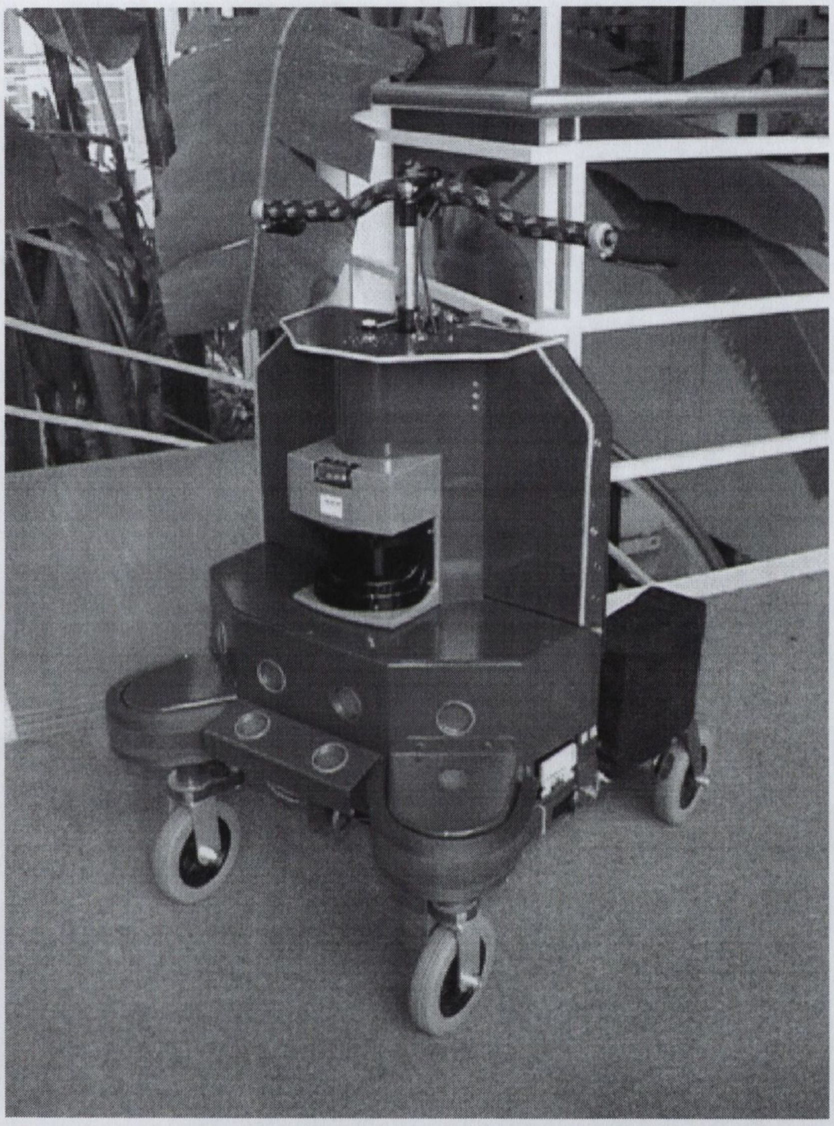


Figure 1.1: The Passive PAM-AID - **P**ersonal **A**daptive **M**obility Aid

can easily lead to a very inactive lifestyle which can result in other health problems. Thus, a mobility aid which provides a user with the possibility of safe mobility can be of enormous benefit.

Field and service robots are attempting to address very important needs in the healthcare industry. Service robots have reached a stage where they are now sharing workspaces with humans to a greater degree than ever before. This is especially true in the area of robotic assisted surgery [15] where critical tasks are performed by robots to a much higher degree of precision and efficiency than can be achieved by humans. With the significant advances in robotics and sensing, this technology is gradually becoming more accessible to individuals at a more personal level. Smart wheelchairs are being developed for people with severe physical handicaps [16, 47, 46, 63], smart workstations are making it possible for people to return to the workplace [24, 27]. The design of robotic aids specifically for the needs of the disabled and elderly, however, is still very much in its infancy. One important reason for this is the difficulty in engineering for a group of people which is far from homogeneous. If a device is to be acceptable to as large a user group as possible, one must take into account the physical and cognitive limitations that sometimes ensue accompany disability or old age. The designer has to aim for simplicity without loss of functionality, robustness, reliability and above all safety. While these are general attributes of good design they become especially significant when engineering for more vulnerable groups in society. This research attempts to address the needs of elderly people with both a mobility impairment and a

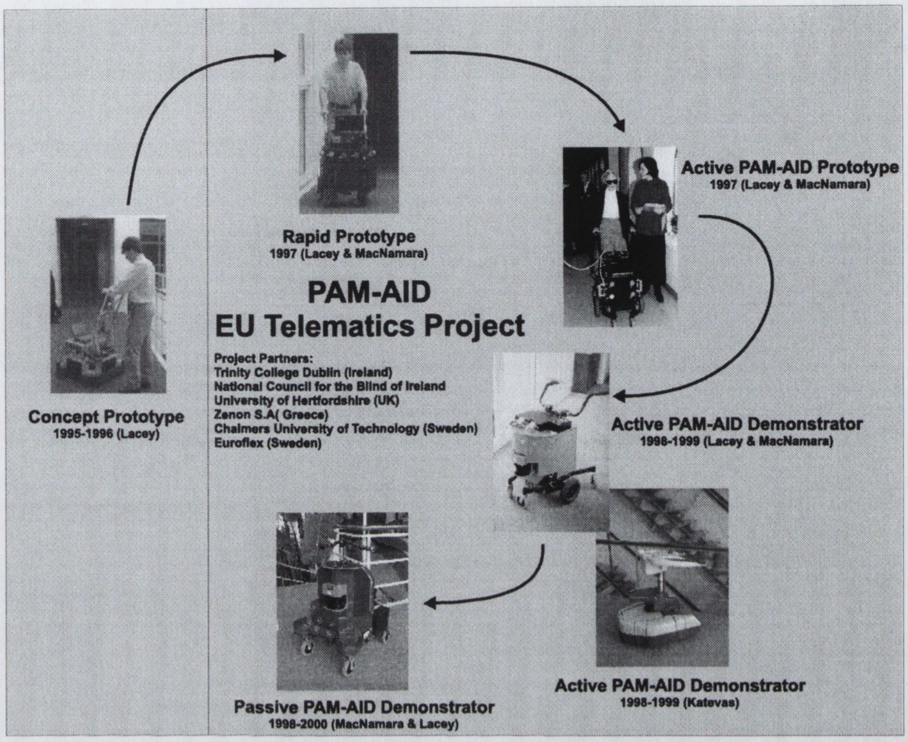


Figure 1.2: History of PAM-AID Development

visual impairment. This places huge constraints on the design of the system as a whole, but especially on the user interface. Most of the potential users will have lost their sight later in life and would not be familiar with communication devices such as braille keys. The choice of feedback modalities is severely curtailed and as a result much high level information processing has to be carried out to provide the user with appropriate information. Context becomes extremely important when attempting to filter the information being relayed to the user.

When designing for the elderly, frequent evaluations by individuals from the targeted user group are essential. For the PAM-AID, this resulted in an evolutionary design and development process as shown in Figure 1.2. The PAM-AID concept was the focus of a European TIDE (Telematics Initiative for the Disabled and Elderly) project from 1997-1999. Both the active and passive prototypes shown in Figure 1.2 were developed within the framework of this project. An additional active PAM-AID prototype was developed by one of the project's industrial partners using their own proprietary software.

The idea for the passive PAM-AID concept, which is central to this thesis, came from observations at a usability trial of the active PAM-AID concept [54]. The active PAM-AID is a powered rollator which has similar functionality to the passive system but can also function as an autonomous, general purpose robot in the absence of the user. What was apparent from this trial was the difficulty is guaranteeing the safety of the user from coming into contact with objects in the environment. Although sensor redundancy and maximum sensor coverage was a priority, complete sensor coverage of the space through which the user moves was extremely difficult to achieve. The sensors are mounted on the mobility device while the user is not completely surrounded by the device. If the system were not aware of contact between the user and an object in the environment, injury could result. A passive device reduces considerably the risk of injury to the user. Aside from safety, it has other advantages such as a simpler user interface, a significant reduction in weight and power consumption. A photograph of the final version of the passive PAM-AID is shown in Figure 1.1.

While mechanical design is of great importance, it is only one facet of the entire system. Accurate sensing and robust navigation are also intrinsic components of the system. One of the main goals of the thesis was to give the targeted user group more *independent* mobility. From the robotics view point, this corresponds to a robot with good navigation capability. General obstacle avoidance routines are efficient and work well on a mobility aid such as wheelchair or walker as long as the user does not want to interact with the objects in the environment. Realistically, however, people need to interact with their environment. A user will want to park the aid beside a chair, under a table or in a corner out of the way of their present activities. General obstacle avoidance routines perform poorly in these circumstances, especially if the kinematics of the robot constrain motion and the obstacle density around the robot is high. In situations like this it maybe necessary for the user to perform a simple manoeuvre. This thesis addresses this need. A manoeuvre planner was developed which takes into account the kinematics and the dynamics of the user and the robot as a complete system. The idea of taking user kinematics into account might seem somewhat odd but can be explained as follows. The very frail have a fear of walking backwards as they are prone to falling because of lack of support. This is an example of constraint which is psychologically imposed rather than a result of pure physical limitations. Any manoeuvre planner developed must explicitly take such factors into account. This again highlights the impact of human factors on the design process and the real need to work closely with potential end users.

The richness of data from the PAM-AID user interface depends on the sophistication of the sensing used. The current PAM-AID has a simple analog sensor capable of measuring steering angle. With more sophisticated multi-axis force sensing a wealth of information about the user becomes available. For instance, the dynamic loading of the PAM-AID can be used to infer gait information. Gait, posture and balance are intrinsic components of a persons ability to ambulate efficiently [106]. A myriad of techniques already exist to measure gait characteristics. They all, however, require that the person under observation be evaluated in a specialized gait laboratory or at least have some sort of foot switch placed inside the shoe. Embedding sensing into mobility aids means that the user is not required to have any monitoring device attached to themselves. Monitoring is thus very unintrusive and long term monitoring is possible.

1.2 Thesis Structure

Chapter 2 provides background information and sets the context within which the PAM-AID system was developed. Statistics are provided which illustrate how many people are affected by both a visual impairment and a mobility impairment. Projected statistics for the next fifty years are also presented. These statistics aim to show the potential the PAM-AID has both now and in the future. This is followed by a general overview of the area of assistive technology for the visually impaired. Various different electronic travel aids are discussed along with the state of the art in robotic systems. The field of local navigation as applied to rehabilitation robotics is reviewed. Strategies for dealing with fine motion planning with uncertainty are discussed in depth.

Chapter 3 describes the system in detail. The chapter begins with an in-depth description of the mechanical design. It was attempted to keep the mechanical design as simple as possible while at the same time providing the high manoeuvrability that is necessary for indoor use. Different mobility module designs are reviewed with this in mind. The hardware and software architectures are presented. Various different sensor configurations were experimented with and these are described along with their respective navigation algorithms. Finally the feature extraction module used on the system is presented briefly.

Chapters 4 and 5 discuss the manoeuvre planner and cooperative trajectory execution module. This module can be evoked by the user when the navigator reports that it cannot find a free path. It will plan a path out of the dead-end, taking into account the dynamic behaviour of the user and the robot as a whole. Elderly people are discouraged from walking backwards, so the planner will attempt to return manoeuvres such that the amount of reversing required is kept to a minimum.

Chapter 6 presents the results of the iterative design phases. The PAM-AID was evaluated extensively by real users during the design process. In all, four usability trials were carried out. The outcomes of each trial is presented in detail with special emphasis on the final Irish trial in which the manoeuvre planner was evaluated.

Chapter 7 describes preliminary research carried out in the area of health monitoring. Experiments were carried out to demonstrate that certain gait parameters of the user could be measured with a robotic mobility aid such as the PAM-AID. This research was not actually conducted on the PAM-AID, but on a similar research platform which was constructed while working as a visiting researcher at MIT. Chapter 8 concludes the thesis and provides a summary of the main findings of the research. Possible directions for future research are also discussed.

1.3 Contributions of the Thesis

To summarise, the contributions of this work have been as follows:

- The design and construction of a novel robotic mobility aid for the frail visually-impaired.
- A manoeuvre planner which can assist the user when general obstacle avoidance fails.
- An adaptive, dynamic model of the user which is used in conjunction with the manoeuvre planner
- Preliminary investigations into the use of the device for health monitoring, specifically gait analysis.

In addition, this research has succeeded in introducing state of the art technology to the elderly without overwhelming them with complexity. This was achieved to a large extent through the involvement of *real* end-users in every stage of the design and development process. The choice of a mechanically passive system was demonstrated to promote a good synergy between user and machine and at the same time reduce user inhibitions. Such progress is important if robots and people are to coexist in shared workspaces.

Chapter 2

Background

2.1 Overview

A significant portion of the elderly population is affected by visual impairment. A detailed account of the extent of visual impairment in the elderly population and how it affects everyday activities is presented in the first part of this chapter. Visually impaired people have used a variety of methods for improving their mobility. More conventional methods have been complemented by a wide variety of electronic travel aids which have met with varying success. These are discussed in Section 2.3. Also discussed are state of the art robotic aids designed for the visually impaired and for the elderly, albeit as distinct and separate groups. Dual disability, however complicates matters to the extent that none of the reviewed systems can fulfil their requirements. The chapter goes on to review local planning methods and fine-motion planning where uncertainty plays a role.

2.2 Profile of Potential End Users

The human vision system provides the most precise information about the position of the one's body relative to the outside world. It is the most important sensory modality in terms of safe navigation of our environment and interaction with objects in the environment. Diseases such as cataracts, macular degeneration and glaucoma are prevalent in the elderly. Visual acuity, peripheral vision, depth perception, accomodation, adaptation to darkness and contrast can be impaired. In healthy individuals there is a redundancy in sensory function. Even if failure occurs in one of the sensory organs, the individual is able to compensate. For instance, a young person with a visual impairment can rely on vestibular and proprioceptive feedback to maintain balance. In the elderly population, a general degradation of the sensory and motor functions occurs. A visually impaired person with decreased proprioceptive and vestibular sensing will find it much harder to retain his balance and is therefore more susceptible to falls. Mobility becomes hazardous and assistance is required.

2.2.1 Current Statistics

Comprehensive statistics on dual disabilities are rare. Some studies do provide compelling evidence that there is a substantial group of elderly people with both a visual-impairment and mobility difficulties. Ficke [34] reported that there are approximately 1.5 million people resident in nursing homes in the United States of which 88% are over the age of 65 and 40% are over the age of

85. Of those 1.5 million people, 22.7% are visually impaired and 70.7% required some form of mobility assistance. The incidence of visual impairment increased with age, 14.3% of those aged between 65 and 74 had a visual impairment and this rose to 30.8% among people aged 85 and over. The number of people affected by a mobility impairment also increased significantly with age from 60% in the 65-74 age group and 81.6% for those aged 85 and over. Rubin and Salive [89] report on a number of population based studies which also indicate a strong correlation between sensory impairment and physical disabilities. Dunn et al. [29] provides evidence for the increased risk of falls as a result of a visual disability. This is echoed by Campbell et al. in [20]. They describe the effects of visual impairment on the ability of the person to tackle Activities of Daily Living (ADL) and their susceptibility to other illnesses as a result of the visual impairment. A summary of the findings of this report are provided in Table 2.1. Of particular relevance to the work described in this thesis is the increase in difficulty walking (43.3% versus 20.2%), the increase in the susceptibility to falls (31.2% versus 19.2%) and the increased number of hip fractures (7.1% versus 4.2%).

2.2.2 Forecasted Statistics

Statistics from the U.S. Bureau of the Census [85] estimate that the population of people in the United States aged 65+ will more than double by 2050 to approximately 82 million. Anticipating this large increase in population, government bodies are putting together strategic plans to deal with long-term

Category	Reported impairment %	(95% CI)	No impairment %	(95% CI)
Activity limitations				
Difficulty walking	43.3	(±2.5)	20.2	(±1.0)
Difficulty getting outside	28.6	(±2.3)	10.4	(±0.8)
Difficulty getting into and out of bed or a chair	22.1	(±2.5)	9.3	(±0.7)
Difficulty managing medicine	11.8	(±1.7)	4.4	(±1.0)
Difficulty preparing meals	18.7	(±2.2)	6.7	(±0.7)
Secondary health conditions				
Falls (previous 12 months)	31.2	(±2.5)	19.2	(±1.0)
Broken hip	7.1	(±1.3)	4.2	(±0.5)
Hypertension	53.7	(±2.7)	43.1	(±1.3)
Heart disease	30.2	(±2.7)	19.7	(±1.0)
Stroke	17.4	(±1.8)	7.3	(±0.7)

Table adapted from [20]. Total population 8,167

Table 2.1: Secondary Effects of Visual Impairment on the Frail Eldery

care for the elderly in an age where the elderly population are more likely to be living alone and less likely to have family care-givers. One such step in that direction came with the passing of the Technology Related Assistance Act of 1988 by the US House of Congress. The aim of the act was to expand the availability of assistive technology services and devices to people with disabilities.

2.3 Travel Aids For Visually Impaired People

Travel aids for the visually impaired range from the conventional white cane, through hand-held ranging devices to state of the art robots. This section discusses a representative selection of these travel aids with special emphasis on those which have been clinically tested by government agencies such as the Department of Veterans Affairs in the United States.

2.3.1 Conventional Aids

The Long Cane

The long cane is probably the most popular and cost-effective mobility aid for VIPs. The cane as a navigation aid had existed for a long time, but it wasn't until 1964, under the leadership of Russell C. Williams of the Veteran's Administration, that formal specifications for its design and use were published. Farmer in [33] describes the most desirable features in detail. Important features include the length and weight of the cane. The cane should be long enough to provide the user with ample time to react to objects in his path. Proper use of the cane involves sweeping the area in front of the user. The sweeping action is synchronized with the gait of the user. Also of importance is the tactile and aural response from the cane. This puts restrictions on the material used in the cane. It must be rigid enough so that vibrations caused by different surfaces are not damped beyond recognition.

The main disadvantage of the long cane is that it provides no warning of impending collisions of the user's upper body with obstacles. Also, the information from the cane is very local and only covers the next stride of the user.

The Guide Dog

Guide dogs are used very successfully by able-bodied VIPs. They have the added advantage of having the ability to learn to recognise features in the environment that are of special significance to the the VIP. A potential user needs to be profoundly blind for a guide dog to function effectively. If the owner were constantly overriding the decisions of the guide dog, its role as a navigation aid would no longer be clearly defined. A guide dog moves more comfortably at the walking pace of an able-bodied person. The user needs sufficient strength to handle it and to look after it on a day to day basis. They are thus ill-suited as an aid for frail people.

2.3.2 Electronic Travel Aids

Many electronic travel aids (ETA's) have been devised in the past 40 years. The more successful have been developed by, or in close cooperation with mobility specialists. For an ETA to be of genuine use to VIPs it must fulfil a number of requirements. It should be able to detect obstacles and specify their approximate location. It should have the capability to detect down drops. The feedback from the device should be easy to interpret and require minimal training. The device should not impede general mobility and should not in any way interfere with the users own ability to sense the environment. Physically the device should not be cumbersome, it must be energy efficient and have minimum visual impact. Distinction should also be made between primary and secondary ETAs. Primary ETAs are aids which can be used by themselves for navigation. Secondary aids must be used in conjunction with primary aids and would be used to complement the primary aid's functionality. Only a small number of devices have been clinically evaluated. The devices described in detail below have all been evaluated by the Department of Veterans Affairs in the United States.

Laser Cane

Technical advances in the 60's such as solid-state GaAs lasers, fresnel lenses and NiCd batteries allowed for the embedding of a laser ranging system in a long cane. The laser cane was developed in an attempt to overcome some of the shortcomings of the standard long cane. As was mentioned previously, the standard long cane provides no prior warning of obstacles above waist height.

The C5 laser cane [9] has three solid-state lasers mounted inline in the cane body. One laser is used for detection of head-height obstacles, the second for obstacles in the direct travel path and the third is pointed downwards to detect down-drops. The feedback to the user is transmitted tactily (part of the handle vibrates under certain obstacle conditions) and also in the form of audible tones.

The limitations of the laser cane are primarily due to the designer's over-reliance on one sensor type. The laser will function well in most environments but is unreliable when presented with materials which are very transparent such as glass and perspex. The surface texture also has an influence on the strength of the laser return. Very smooth surfaces will tend to reflect the light specularly, thus no laser return will be detected. This has severe implications on the reliability of the down-drop sensor. Problems also exist when used in inclement weather. Snow and rain may cause erroneous laser returns.

The SonicGuide and Sonic Pathfinder

The SonicGuide was developed by Leslie Kay in 1966 [48]. It uses broadband sonar technology. The sonars are head-mounted and the feedback to the user is in the form of a stereo audio image. A transfer function converts the sonar distance estimation to an audible stereophonic signal. The SonicGuide also allows an experienced user to differentiate between different surface textures. Smooth surfaces would have a purer tonal response than rough surfaces. When properly interpreted, the information from the SonicGuide is potentially much more powerful than that from the laser cane. The laser cane will only let the user know if an object is present whereas a experienced SonarGuide user will have more information on the object distance and of the nature of the object. Proficient use of the sonic guide requires intensive training due to the complexity of the sound image presented to the user.

The Sonic Pathfinder[43] also consists of a head-mounted sonar array consisting of two transmitting and three receiving transducers. It uses the tonal progression of a musical scale to indicate proximity to an obstacle. It was developed at the Blind Mobility Research Unit at Nottingham University, England. Unlike the SonicGuide, it does not provide the user with information on surface texture. It uses AI decision making techniques to prioritize information relayed to the user. A more complete list of ETA's is listed in Table 2.2 along with a short description of how they function.

Table 2.2: Electronic Aids for the Visually Impaired

Device Name	*Description*
C5 LaserCane	A long cane with three embedded lasers using optical triangulation to detect objects at head height, objects in front of the user and drop-offs
The Talking Cane	A long cane with a laser bar code reader. Bar codes are placed stategically in users environment. User gets audio feedback on current location
The Sonic Pathfinder	A secondary mobility aid. Consists of a head-mounted sonar array. User gets audio feedback on position of obstacles
KASPA	Head mounted wide angle sonar array with an addition high resolution 'foveal' sonar element for improved localization of obstacles. Comprehension of audio feedback can be challenging
Mowat	A handheld ultrasonic device. The device will vibrate more intensely, the closer an object is. The device also produces a tonal output. The closer the object, the higher the tone pitch
Sensory 6	Sonar transducers are mounted on spectacles. User receives audio feedback as to proximity of obstacles
Wheelchair Pathfinder	Wheelchair mounted sonar modules used to warn user of obstacles within a distance of 1 foot. Can be used for wall following

Recent advances in microfabrication technology mean that construction of very large scale arrays of light sensitive elements is now possible. Researchers are attempting to use this technology for the purposes of developing a retinal prosthesis[107]. This work is however in its infancy and will require intensive research before the first human implant can take place.

2.3.3 Robotic Guides

Over the past few years, a number of robotic devices have emerged that attempt to address the needs of the visually impaired and the elderly albeit as separate problems. All the systems described are still in the prototype stage of development.

The GuideCane was developed at the University of Michigan by Borenstein and Ulrich [14]. A sensor head with wheels is mounted on the end of the cane. The GuideCane is pushed and will steer around obstacles based on the processed sensor data. Its major disadvantage is its weight when going up or down stairs. The device is still in the prototype stage. The Navbelt [93], although not a robot in the strict sense, does employ robot navigation techniques. It consists of an array of sonar transducers worn around the waist. Feedback consists of a panoramic auditory sweep from left to right. The amplitude of the auditory output during a sweep is a function of the obstacle density at that particular angle to the users current direction of motion.

Mori et al. [73] built a guide-dog robot called Harunobu-5. The device is based around a Suzuki scooter. It uses both vision and sonar sensors for navigation. The user controls the device velocity by pushing or pulling on a bar. The system has speech output and recognizes a limited vocabulary. The whole system is physically very large (720mm wide and 1460mm long).

The Movaid robot[25] was designed as a domestic aid for the elderly and disabled. It consists of an 8-DOF manipulator arm mounted on a mobile base. It was developed to provide increased accessibility to household technological appliances such as cooking facilities. Care-O-bot [90] is a similar system which is currently in development. It is a robotic aid for elderly people in their home environment. It is being designed to perform simple household tasks and provide health management.

The PAMM (Personal Aid for Mobility and Health Monitoring) [28] is designed to delay the transition from assisted living facilities to nursing homes. Its current configuration is that of a smart cane. It navigates by following signposts placed regularly on the ceiling of a facility. It also uses ultrasonic sensors for obstacle avoidance. Similar to this system is one that has been developed by Hitachi [74]. The system has been developed for the general frail elderly population. One notable feature of the system is the provision of a mechanism by which the user is assisted in transferring from sitting to standing or visa versa. This device has also been adapted so that it can be used by people suffering from hemiplegia [30].

None of the devices described in the previous sections have been designed specifically with the frail, visually impaired in mind. Neither the c-5 laser cane or the GuideCane can give potential users the physical support they require. The SonicGuide, the Sonic Pathfinder and the Navbelt produce quite complicated audio feedback which most elderly people would find difficult to comprehend. The Movaid system can navigate autonomously in domestic environments but was not designed to guide a person around such an environment.

2.4 Path Planning

Any mobile robot must have the ability to plan paths and navigate successfully within its workspace. Researchers have simplified this very complex task somewhat by using robots which are omni-directional. A robot platform with omni-directional capability can instantaneously change its direction of motion and can follow an arbitrary path in its workspace. For omni-directionality to be realized, the system must be holonomic. The definition of a holonomic system is one in which the number of degrees of freedom are equal to the number of coordinates needed to specify the configuration of the system. Examples of platforms which exhibit this behaviour include the robots Romeo and Juliet developed by Stanford Robotics Laboratory in association with Nomadic Technologies[1]. These robots have turrets which can rotate independent of the robot bases allowing for optimal positioning of sensors. When dealing with a human-centred system however huge constraints may be imposed on sensor layout and device kinematics. In the area of rehabilitation robotics, the mobile robots developed generally do not boast the omni-directional kinematics of research robots. Omni-directional drives require locally flat surfaces such that all the drive wheels are providing traction. They are in general heavier and require much more sophisticated drive electronics. They do not

[1]Nomadic Technologies, Mountain View, CA

handle saddle boards, uneven footpaths, curbs etc. very well. Thus, most developers of smart wheelchairs etc. have stayed with more traditional kinematic arrangements such as electrical differential drives. In terms of navigation and planning, the kinematic constraints of a non-holonomic device must be carefully taken into account.

2.4.1 Planners for Human-Centered Mobile Robots

Various local planner and general obstacle avoidance algorithms have been applied to devices which aim to assist people with disabilities. Many algorithms have used Borenstein's Vector Field Histogram(VFH)[12] as a starting point. The algorithm is attractive as it provides very efficient, real-time collision avoidance. The algorithm allows goal-directed behaviour where the user, through the user interface, can specify the goal as a preferred heading direction. The NavChair project [7] adapted the VFH (non-point robot version [13]) for the purpose of providing general obstacle avoidance support for a severely disabled wheelchair user. The raw VFH algorithm allows travel through relatively cluttered workspaces with only minor reductions in speed. It means however that angular accelerations can be high. This type of behaviour is quite unsettling for a wheelchair user. The new algorithm, called the *Minimum Vector Field Histogram* slows the chair down by an amount proportional to the difference between the command direction and the direction of travel. In this way, the user can feel that the system is close to an obstacle. It also uses a risk assessment metric to control the amount of freedom the wheelchair user has.

This depends on the obstacle density surrounding the robot. Whether a task will succeed or not will depend on the arrangement of the obstacles. The original VFH algorithm did not explicitly take the width of the robot into account. As a result, collision free trajectories could not be guaranteed. The VFH+ algorithm[99] introduced many improvements to the basic algorithm. It uses a C-space representation of the robot workspace. Obstacles are enlarged by the robot radius and the robot can thus be represented as a point in this space. The robot kinematics are explicitly taken into account and potential trajectories are checked for collisions before being executed. This algorithm was used very successfully on the GuideCane which was described in Section 2.3.3. The SENARIO wheelchair [47] also uses a modified VFH. The Active Kinematic Histogram (AKH) as it is called, addresses a number of issues including the kinematic constraints of the robot. It does not assume a symmetric, point robot as is the case for the VFH and also attempts to deal with unpredictable dynamic behaviour which results from swivel castors not behaving in an ideal manner when under load.

Alternatives to the potential field methods for local obstacle avoidance include the Curvature-Velocity Method of Simmons [95]. He formulates the problem as one of constrained optimisation in the 2-D velocity space of the robot (the two orthogonal dimensions of velocity space are the translational and rotational velocities). It is assumed that the robot travels along arcs of circles. Constraints include the maximum safe velocity and the distance to obstacles along a particular trajectory arc. The optimisation of the vehicle trajectory is achieved by maximising a weighted function which trades off goal-directedness, safety and speed. The algorithm is suitable for a range of non-holonomic vehicles including those using differential drives, synchro-drives and car-like robots. The advantage of this method over the original VFH method is that it explicitly takes the kinematics and dynamics of the vehicle into account (as does the VFH+). The Curvature-Velocity Method does have some similarity to the VFH in that sensor evidence is built up using a histogram grid.

A distinction should be made at this stage between general obstacle avoidance and fine motion manoeuvre planning. Approximating the system by a bounded disk is appropriate for low obstacle densities. In environments of high obstacle density however, a more exact representation of *system*[2] dimensions and kinematics are required for successful navigation and the data reduction techniques of potential field methods such as the VFH are no longer as appropriate.

Realistically, users of robotic mobility aids will want to interact with objects in the environment. The object in question might be a table or a chair. In such instances, the possibility must exist to switch out of general obstacle avoidance routine in order for the user to achieve their goal. On returning to the general obstacle avoidance mode, the system may fail because obstacle density is too high. An real example of such a situation is shown in Figure 2.1. Here, the PAM-AID is in a corner beside a table. For the user to return to the

[2]The term *system* is used instead of robot to emphasize that the constraints imposed by the user may also play a significant role in deciding whether a planned path is feasible or not.

relative free space of the centre of the room, a manoeuvre must be executed. The actual manoeuvre made by the user with the PAM-AID consisting of a reverse translation, followed by a rotation is shown in the diagram. The darker coloured dots represent the trajectory followed into the dead-end. The robot at this point is represented by the shaded box. The sequence of unshaded rectangles represent the motion of the robot while escaping from the dead-end. The obstacle clearance at one point is a mere 2cm. For these types of scenarios, a more exact form of planning strategy is required. The next section reviews more exact planning methods for non-holonomic systems.

2.4.2 Motion Planning for Non-Holonomic Systems

The field of fine motion planning has been researched at length. Early research focused on path planning for holonomic or free-flying robots i.e. robots which can instantaneously change their direction of motion. A battery of planning techniques have been developed for these systems. An excellent review is provided by Latombe in [58]. He distinguishes between global and local planning methods. Global planning methods are defined as those methods that determine the global connectivity of free space as a preprocessing step. The planning then involves searching the graph for a path between initial and goal states. Local methods, on the other hand, avoid this preprocessing step. An adjacency graph is produced, where each node in the graph represents a configuration in the configuration space of the robot. Planning involves finding a connected path from the initial robot configuration to the goal configura-

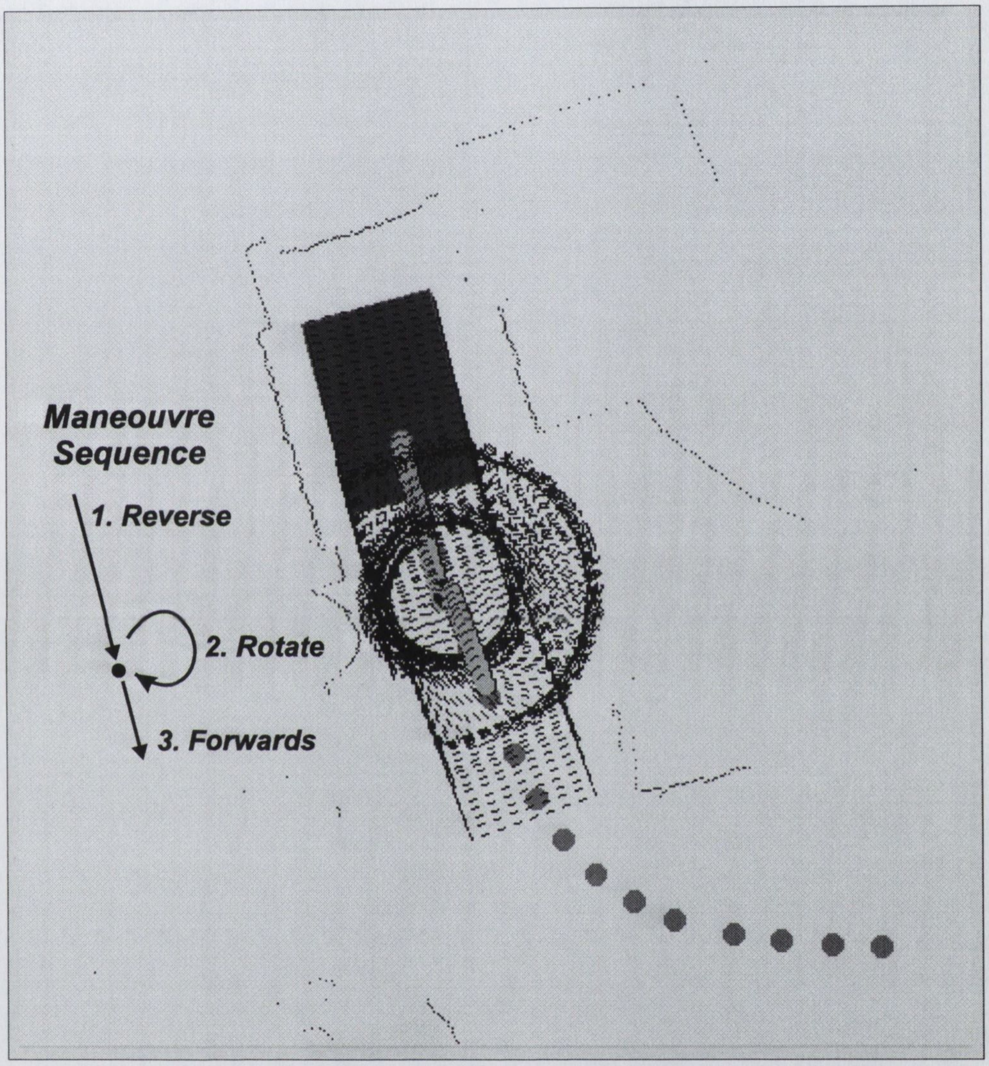


Figure 2.1: Typical manoeuvre required in an environment of high obstacle density

tion. The search space for local methods is of a much higher dimension than for global methods. Normally powerful heuristics such as gradient descent of a potential field are used to drive the search. These techniques in their raw form assume that the robot following the planned path can follow an arbitrary curve produced by the planner. In general, however vehicles outside the research community are non-holonomic and extra manoeuvres are required to adhere to a path. A well-know scenario is that of parallel parking a car. Here, the vehicle must complete a series of forward and reverse motions with appropriate steering angles. An example of an autonomous system which can carry out such a parallel parking manoeuvre is described in [82].

Laumond [60] developed a two phase approach to nonholonomic planning. In the first phase, a feasible path for a holonomic vehicle is planned. In the second phase, sections of the path which cannot be traversed by the non-holonomic vehicle are replaced with manoeuvres which the vehicle can execute. These manoeuvres take the form of Reeds-Shepps curves [87]. A completely different approach is taken by Latombe in [58]. The robot configuration space $\Re^2 \times [0, 2\pi)$ is descretized into an array of rectangloids. Rectangloids are adjacent if a path exists between the configuration represented by the first rectangloid and the configuration represented by the second. A graph is produced whose nodes are the rectangloids. The graph is searched using an A* algorithm for a feasible path between two configurations. Latombe adopts a hybrid approach in [57]. He uses a two phase approach similar to Laumond. The first phase uses a holonomic planner based on the potential field approach which produces a set of curves called the *skeleton* which is akin to the generalised Voronoi diagram. The second phase consists again of substituting in feasible manoeuvres which satisfy the kinematic constraints of the vehicle.

2.4.3 Planning with Uncertainty

Uncertainty in sensing and control are an integral part of robotics. For an autonomous robot with sophisticated motor control, trajectory following can be extremely accurate and uncertainty in robot positioning need not be of any concern [37, 59]. This is especially true in carefully controlled environments where wheel-slippage is negligible and dead-reckoning is very reliable. This is however certainly not the case in more hostile environments such as those experienced by planetary rovers. In other systems, planning with noisy or incomplete range data can also mean that uncertainty has to be explicitly modelled. In the case of the PAM-AID, the principle source of uncertainty is in the dynamics of the user. This can increase the complexity of the planning process considerably. It is not sufficient to produce just one plan - a whole suite of solutions which reflect the uncertainty in motion must be calculated.

Uncertainty in robot planning has been dealt with in a variety of ways. In general, if goal positioning does not have to be too precise, the obstacles in the robot's configuration space are grown slightly and a path is planned among these augmented obstacles. This method can introduce problems if the workspace of the robot is cluttered. Augmenting obstacle size can result in thin connecting areas of free space being consumed. Thus, connecting paths which previously existed are no longer present and the planning algorithm cannot return a valid path. In these situations, it is normal to combine sensing with planning to reduce uncertainty. Lazanas in [61] discusses the use of recognisable *landmarks* which are easily and robustly identifiable by the robot sensor system and which can be used to reach the goal precisely.

Lozano-Perez in [65] describes a general approach to planning with uncertainty - *preimage backchaining*. The preimage is region of the configuration space from which the execution of a motion command will result in the reaching of a goal recognizably[3]. The preimage concept can be expressed more formally as follows:

Let G be a goal region in the robot's valid configuration space C_{valid}. Let $M = (\overrightarrow{v}, TC)$ be a motion command where $\overrightarrow{v}$ is the velocity vector TC is the terminating condition. The preimage P, of G is the subspace of C_{valid} such that on execution of the motion command M, the robot is guaranteed to reach G and TC ensures that robot motion terminates within the goal subspace G.

Figure 2.2 illustrates this preimage concept. The Figure on the left shows the goal, the current position of the point robot, the velocity vector and the uncertainty in direction associated with the vector for a particular motion command. The preimage approach assumes that this uncertainty is known. The terminating condition is normally determined by a sensor returning a certain condition e.g. no motion is detected for a maximum applied force. The

[3]The system must be able to determine whether the goal has been reached or not.

planner needs to know the configuration subspace from which it is guaranteed that the robot will reach its goal location given the velocity vector, its associated uncertainty and the terminating condition. This subspace is shown in Figure 2.2b. Lozano-Perez refers to this subspace as the *preimage* of the goal. The task being performed in this example is essentially a peg-in-hole insertion problem. The actuator exhibits force-compliant control and the contact space is frictionless. Thus, motion is still possible on contact with a surface providing some component of the applied force is parallel to the surface at the point of contact. This is indeed what would happen if the peg came into contact with the surface to the right of the hole in the example.

Backchaining of preimages is necessary when more than one discrete motion command is necessary to reach the goal. An example of this is shown in Figure 2.3. The diagram on the left shows the initial position of the block along with the intended goal position. The block cannot be moved from its initial position to the goal position with one motion command. To begin, a command velocity $v1$ is selected and its preimage is computed. If this preimage does not contain $Init$, it is used as an intermediate goal for another selected velocity command, $v2$. The preimage $P2$ of $P1$ for velocity command $v2$ is computed and again checked to see if it contains $Init$. The diagram on the right of the figure shows that with the combination of the velocity command $v2$ followed by $v1$, the goal is indeed reached. This methodology can then be extended to a general n-step case. If P_n is the n^{th} preimage, then P_n is the preimage of the intermediate goal P_{n-1} for the motion command M_n. P_{n-1}

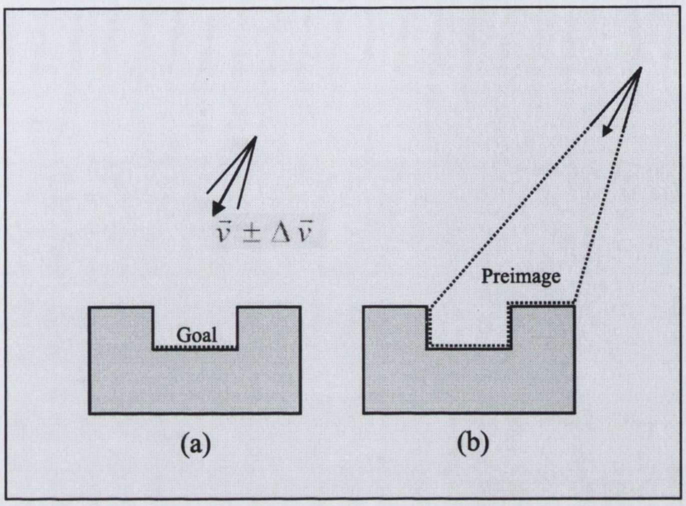


Figure 2.2: (a) The planner Goal. (b) The preimage of the Goal for a vector $\vec{v}$ with uncertainty $\pm\Delta\vec{v}$

is in turn the preimage of intermediate goal P_{n-2} for the motion command M_{n-1}. P_0 is the actual goal. The reverse sequence of motion commands $\{M_n, M_{n-1}, ..., M_2, M_1\}$ is then the n-step motion strategy. In general, given a set of possible motion commands, an optimal subset of commands are compiled together to get from the initial state to the goal state by searching a tree of preimages. The search algorithm might employ an optimization cost-function to minimise the length of the planned path, the time taken to complete the path or the number of discrete motion commands.

2.5 Modelling the User

With robots operating in the same workspaces as humans, the need for good characterisation of the dynamics of the system as a whole is becoming more

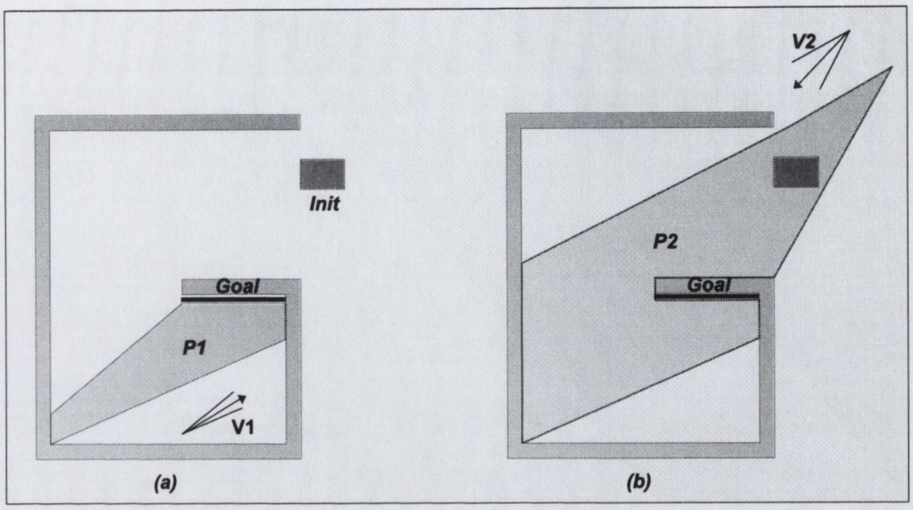


Figure 2.3: Sequential Two Step Motion Strategy

important. Safety is one issue and human-machine compatibility is another. They are by no means independent factors in system design. The dynamics of human-machine systems were studied intensively in the 60's and 70's when it became apparent that the stability and performance of high performance machines such as the new generations of fighter aircraft were so pilot-dependent. What was required was a model which could predict the response (output) of a human operator as a function of environment and machine feedback (input). One of the more successful models of manual control with direct application to *pilot-in-the-loop* systems was the crossover model of McRuer [72]. This model represents operator-machine behaviour as a whole rather than as two separate entities. It is based on the observation that trained operators control machines such that the system displays first order dynamics with a time delay. For frequency domain calculations the system can be represented by the following transfer function

$$Y_H Y_C \approx \frac{Ke^{-t_r s}}{s} \tag{2.1}$$

Here $Y_H Y_C$ is the combined open-loop transfer function of human and machine, K is the gain constant. The exponential term is a pure delay with time constant t_r. Classical applications of such a user model are where the user himself is observing the error in position or rate of a system and is then providing input. Results of such experiments are described by Sheridan in [92]. Human operator models have had limited success in real-world applications because of the complexity of operator perception but they have shown to be effective in instrument-driven tasks.

In the field of rehabilitation robotics, some user modelling research has been carried out. Bell [8, 6] developed a method of automatic mode selection based on changes in user behaviour. This method, called *Stimulus Response Modelling*, was applied to the NavChair [7] smart wheelchair. The wheelchair had two modes of operation — general obstacle avoidance mode and door-passage mode. The presence of a door in the wheelchair's local environment was a necessary but insufficient condition for the system to switch from the default obstacle avoidance mode to door-passage mode. The intention of the user had to be ascertained before any mode switch was effected. The system applied a stimulus in the form of a motion command which resulted in the wheelchair moving away from the door. If the user were to oppose this change in direction by applying a joystick input consistent with door passage, the system would automatically change mode and direct the wheelchair through the doorway. The problem of the complexity of operator perception mentioned in the previous paragraph is addressed by this modelling approach in that it is the controller which is providing the stimulus, not some arbitrary entity in the environment. The problem of interpreting a response is more tractable when the system has control over the stimulus.

Harwin in [40], looks at wrist and arm neuro-musculoskeletal dynamics of a human while using a PHANToM arm. He proposes a second order transfer function describing the impedence of the wrist. A non-linear model of the elbow was also developed. Such detailed models are important when designing systems which operate with or at even in the same workspace as humans. A fundamental issue is the measurability of model parameters. This will be discussed later in the context of modelling the stopping behaviour of the PAM-AID.

2.6 Summary

This chapter presented an overview of existing research into navigation and planning with particular reference to applications in human-centered robotics. It also examined the role of user modelling in the performance of human-machine systems. This facilitates a detailed discussion of the PAM-AID manoeuvre planner and trajectory execution module later on in the thesis. The next chapter introduces various aspects of the passive PAM-AID, including the mechanical design, controller architecture and navigation system.

Chapter 3

System Design

3.1 Introduction

This chapter describes the different facets of the general system design. A good mechanical design is of tremendous importance for the success of the entire system. Good sensing and control is entirely superfluous if the mechanical constraints of the device are such that it cannot manoeuvre successfully in typical indoor environments. A tremendous amount of experience was gained from the construction and evaluation of active PAM-AID. The influence of this work on the design of the passive system is presented in Section 3.2. The user interface for the passive PAM-AID is presented in Section 3.4. The philosophy of *less is more* was adopted based on first-hand experience of the abilities and requirements of potential users. The complete software architecture of the final system is presented in Section 3.6. Various general navigation algorithms were experimented with and are described along with their sensor configurations.

Finally, the feature extraction module is briefly described.

3.2 Design Overview

Introducing new technology to the elderly is very challenging. They are by no means a homogeneous group and human factors play a huge role in driving the design. Acceptance of the technology depends both on the potential enhancement of individual autonomy and the visual impact of the devices. A study by Pippen et al. [84] reports that once elderly people get over the initial issues of being dependent on a device, the new level of autonomy gained is of primary importance. Appearance is important but is secondary to the perceived usefulness of the device.

3.2.1 Rapid Prototyping

From the project's inception, it was decided to pursue the path of rapid prototyping and frequent evaluation/design revision cycles, thus making sure that the user was always at the centre of the design process. Rapid prototyping encourages a lot of experimentation before a final design is chosen and highlights potential problems at an early stage in the development cycle. Bailey in [4] attempts to quantify the benefits of prototyping and iterative usability testing. He noted a 12% increase in user performance over each design iteration and an overall improvement of 35% from the initial to the final design. The value of rapid prototyping and frequent user evaluations will be highlighted in the next sections where it is described how design issues in the active PAM-AID

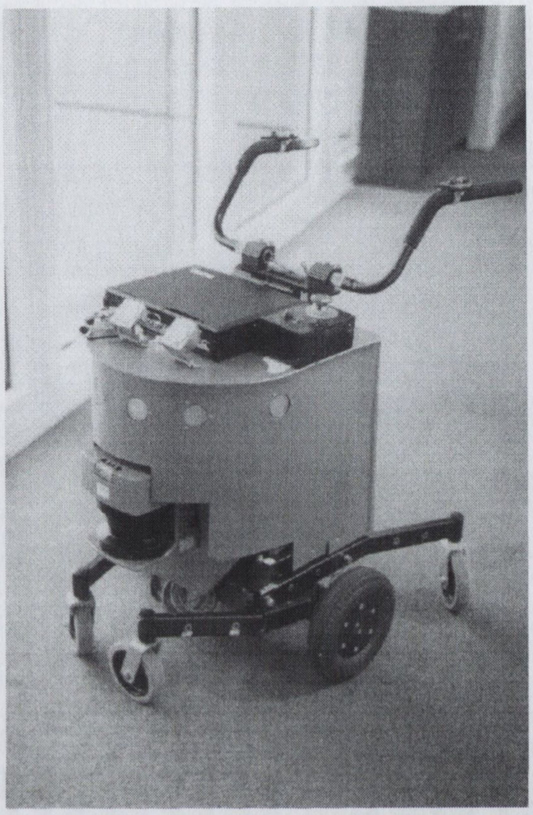


Figure 3.1: Powered PAM-AID Prototype (Active PAM-AID)

prototype were addressed in the design of the passive prototype. A photograph of the active prototype is shown in Figure 3.1. More detailed information on the system can be found in [54].

Active PAM-AID

The active prototypes proved invaluable as a testbed for all facets of the PAM-AID concept. Of particular significance was the experience gained in mechanical and user interface design.

Control of a device which moves under its own power can be quite difficult when the human operating the device is not being transported by the device in question (it is a coupled, articulated system). If the user has reaction times which are slow compared to the response times of the machine, problems arise. This type of behaviour was sometimes observable with the active PAM-AID. Smooth, collaborative motion of the user and machine together was at times difficult to achieve. In the active system, motion was initiated by simply depressing a button. Despite the very gentle acceleration produced by the motion controller, some users were momentarily under pressure to catch up with the machine because their reaction times were so slow. A solution to this problem exists in the form of force sensing coupled with an admittance controller[1][44, 28] but such a system is very expensive to implement [53]. The manoeuvrability of the active prototype was another issue. The chassis used was that of an indoor electric wheelchair with the two drive wheels mounted mid-chassis (see Figure 3.1). While this design provides acceptable performance, it does pose problems when tight manoeuvres are required as the user is never at the centre of rotation of the machine.

The fact that the user and the machine are not locked in the same reference frame also has implications for the design of the interface. On an electric wheelchair, for instance, the user's controlling arm is at rest with respect to the joystick at all times. On a walker, however, only the user's hands

[1]An admittance controller essentially controls the dynamics of the interaction between a manipulator and its environment. In the case of its application to a mobility aid, it controls the dynamic relationship between the force applied by the user and the resulting velocity. The dynamics can be changed to suit the user by changing controller parameters.

are at rest. Joystick style control is difficult (oscillations result due to the lag in user response to the motion of the machine). This issue was addressed on the active prototype by using four discrete switches corresponding to *forwards*, *reverse*, *left turn* and *right turn* respectively. These four switches allowed for very basic motion control but the user still had no control over velocity or the turn radius associated with a turn. The configuration was adequate however for expressing user intentions while the system was in shared control mode but meant manual control was difficult. It was observed in trials that there was some confusion when the user tried to find a particular switch despite using different shaped switches and choosing a spatial layout that had a logical mapping to function (direction of travel).

Another issue that was highlighted in usability trials was the safety implications of introducing a semi-autonomous device with powered actuators into a human workspace. A powered device is, in general, more dangerous than one that is under the power of a human operator. Safety mechanisms are normally more complex and expensive. Sensing has to be more elaborate to protect the user. This is especially true if the user has a visual impairment. A powered system is also a heavier system. It is more difficult to manoeuvre when switched off and is more difficult to transport. The principle components of both the active and passive PAM-AID systems are shown in Figure 3.2.

Passive PAM-AID

The passive PAM-AID concept attempted to redress these issues. By opting for a human-powered device while still maintaining control over steering very

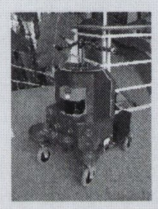
Active PAM-AID (Gerard Lacey) 1997-1999	Passive PAM-AID (Shane MacNamara) 1998-2000
	
Powered Rollator	Mech. Passive Rollator
Windows Platform Multi-threaded	Linux Platform Task Control Architecture
Laser and Sonar Range Sensing	Laser and Sonar Range Sensing
VFH Based Navigation Incorporating Risk Detection	VFH+ Based Navigation
Bayesian Network Feature Detector	Bayesian Network Feature Detector (from Active PAM-AID)
Context-Aware Shared Control	Manoeuvre Planner & Dynamic User Modelling
	Gait Analysis

Figure 3.2: Principle Features of Active and Passive PAM-AID Prototypes

little functionality was lost but many of the problems associated with the active PAM-AID were made more tractable or simply disappeared. Priority was given to certain design criteria which are listed and qualified below.

- **Safety** — It is imperative that the user is safe at all times during the use of the PAM-AID. The user must always feel in control and have the ability to alter the speed of the rollator without having to deal with a complicated user interface. This is especially true if the user needs to stop suddenly. The passive system gives the user this control while still maintaining the capability to navigate safely.

- **Stability** - The PAM-AID must be capable of supporting the user. This should be true not only when the device is being used, as intended, as a mobility aid but also if the user is using the device for support while transferring from a chair. In other words, the device must be statically stable no matter how the user applies a force to the handlebars. Mechanically, this is more readily achievable with four wheels rather than three.

- **Control** - Smooth motion is of paramount importance. The PAM-AID should not make any sudden changes of direction as this alarms the user and could upset their balance. This has important implications for the control algorithms used and ultimately on the choice of sensors. It was for this reason that laser was chosen over sonar as the primary sensor on PAM-AID. This is further discussed in Section 3.8.

- **Manoeuvrability** - For indoor use the rollator must be highly manoeuvrable. Realistic workspaces do not consist of free space with token polygonal obstacles. Environments are dynamic, obstacles are irregularly shaped, space is very confined in places. The device itself must be compact and its kinematics must allow for small turning radii.

- **User Interface** - When designing for the elderly, analogy can sometimes be extremely valuable. For the passive PAM-AID the analogy of the physical interface to a bicycle handlebar was made, no further explaination was required. The handlebar allowed for analog steering and one switch remained to actuate a turn-on-the-spot facility. Thus four switches were replaced by one and discrete control was replaced by analog control.

3.3 Mechanical Design

As mentioned above, one of the key issues in the design of a mobility aid both for indoor and outdoor use is its manoeuvrability. For a powered device there is a trade off between manoeuvrability and complexity. The various possibilities in terms of a basic mobility module are discussed below along with the rationale for choosing the present design. These issues had to be dealt with while considering the various modes of instability that can be inherent is a device that must assist a user with balance, support and tranfer [35].

3.3.1 Review of Mobility Modules

In order for the PAM-AID to have manoeuvrability comparable to that of a standard rollator, the front wheels should emulate the swivel castors used on the front of a standard rollator as much as possible. The two rear wheels should remain fixed to provide lateral stability. A variety of innovative mechanical designs exist which can more or less achieve this. A cobot (cooperative robot) [102] type system is one such design. Cobots are mechanically passive robots designed to work with humans in a shared workspace. The unicycle cobot, as shown in Figure 3.3, consists of a wheel with zero offset (see Figure 3.4c), a 6-axis force torque sensor and a gantry for support. The unicycle has two modes of operation - virtual castor mode and constraint tracking mode. In virtual castor mode, the idea is to try and eliminate the perception of the wheel. This works in all cases except when the linear velocity of the castor is zero and the user applies a force parallel to the wheel axis. The constraint tracking mode introduces virtual boundaries into the workspace of the robot. If the user tries to cross a virtual boundary, the system will prevent the user from doing so and instead force the user to move parallel to the boundary. The system is attractive in that the power which causes the system to move comes from the user alone thus making it a very safe system and very suitable in environments where people could be at risk from the potential malfunction of the system.

While the unicycle cobot is highly manoeuvrable, it is not holonomic. The unicycle cobot has only two degrees of freedom in its three dimensional

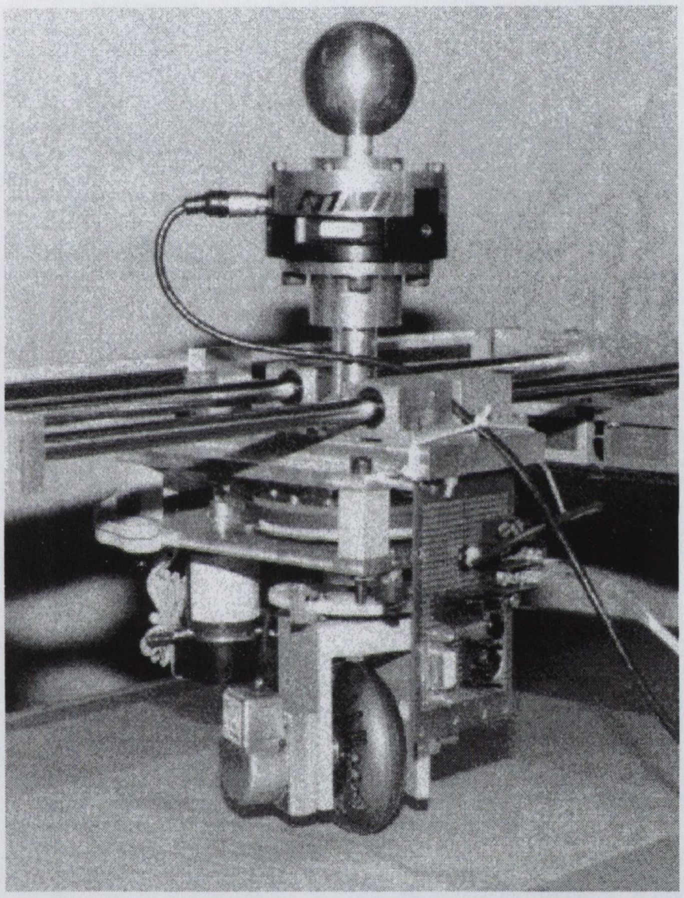


Figure 3.3: Unicycle Cobot, Courtesy of M. Peshkin, Northwestern University

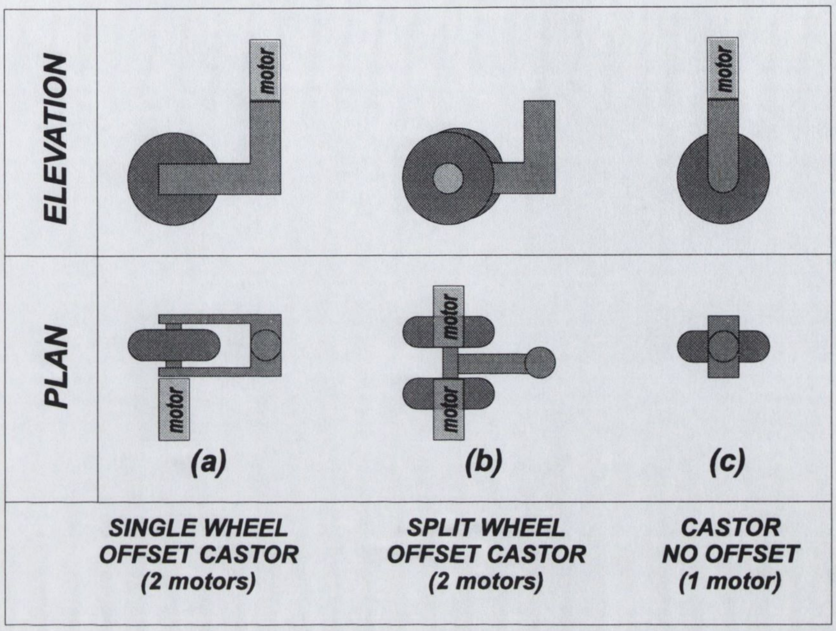


Figure 3.4: Various Castor Module Designs

configuration space (x, y, θ). Holonomic behaviour is desirable as the system is not subject to kinematic constraints which can complicate path planning and control. Driven, offset castors are required for true holonomic behaviour. Systems which use offset castors require two motors, one to control the wheel rotation and the second one to control the wheel velocity. The passive nature of the device is then lost. A single motor cannot be used for controlling the rotation of an offset swivel castor - what will result is rotation of the chassis. An example of a real system using a powered offset castor design (see Figure 3.4a) is described in [45]. This work builds on earlier work by Wada and Mori [101]. To achieve holonomic motion a vehicle requires at least two such powered castor wheels. A variation on this is the split wheel driven castor system of Yu and Dubowsky [108] which also requires two motors (see Figure 3.4b). This system has less problems with scrubbing (slipping) [2] than the single offset castor design. This system demands that all wheels must be contacting the ground for proper operation. It is thus restricted to surfaces which are locally flat or failing that, the castor modules must incorporate a simple suspension system. Both offset castor designs described are active systems in that they provide both powered translation and rotation. The ball wheel of West and Asada [103, 104] is another system that can achieve omnidirectional motion. It consists of at least three spheres, each sphere is driven by one motor. This drive system has been used on an omnidirectional wheelchair [71]. The OMNI wheelchair [46] used Mecanum wheels to achieve omnidirectionality. This mechanism is known to be the source of significant vibration as a continuous point of contact between the wheels and the ground does not exist. It also displays poor odometry. Reviews of wheeled mobile robot kinematics and dynamics are provided in [2, 21].

Thus, in order to obtain castor behaviour with no singularities, two motors per wheel are necessary. The system however ceases to be passive (which has safety implications). If true omnidirectional behaviour were an important issue then it would make sense to choose an offset castor system. Frail, elderly people, however, are not very comfortable moving sideways, diagonally etc., they normally rotate to the direction in which they want to travel and then proceed. Therefore, a mobility aid designed for these people does require high manoeuvrability but is not required to be omnidirectional.

3.3.2 Chassis Description

The mechanical design of the passive PAM-AID is very similar to that of a conventional rollator with a few important differences. The two swivel castor wheels at the front of the walker have been replaced by two wheels whose steering angle is controlled by motors. The motors do not propel the device in any way. A photograph of one of the front wheels is shown in Fig 3.5(b). The motor is offset from the vertical wheel shaft and power transmission is via a drive belt. Absolute encoders return the angular position of each of the front wheels. A position controller is used to adjust the wheel angle to the desired angle. The device has kinematic constraints similar to those of an automobile during normal operation. The non-holonomic kinematic constraints are:

$$-\dot{x}\sin\theta + \dot{y}\cos\theta = 0 \tag{3.1}$$

i.e. the vehicle cannot move perpendicularly to its instantaneous direction of motion. Also, mechanical stops limit the steering angle, ϕ such that:

$$|\phi_{steer}| < \phi_{max} = 68\,\mathrm{deg} \tag{3.2}$$

The relationship between the minimum turn radius, R_{min} and the maximum steering angle is given by:

$$\frac{1}{R_{min}} = \frac{1}{L}\tan\phi_{max} \tag{3.3}$$

where L is the vehicle wheelbase. ϕ_{steer} represents the steering angle of virtual wheel shown in Figure 3.6. The individual wheel angles are denoted by Φ_{master} and Φ_{slave}. The slave wheel tracks the master such that the robot has a unique

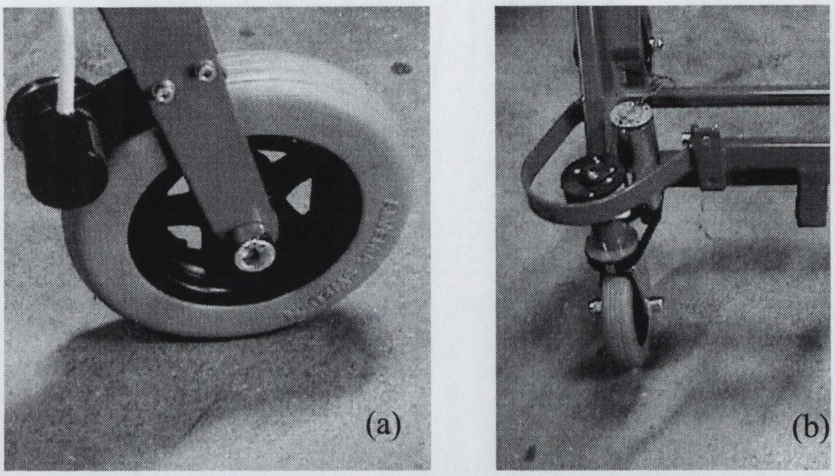


Figure 3.5: (a)Incremental encoder mounting.(b) Motor and Absolute Encoder Assembly

centre of rotation. Given a commanded turn radius, R, the respective steering angles for the master and slave wheels are as follows:

$$\phi_{master} = \arctan \frac{L}{R+d}, \quad \cot \phi_{slave} = \cot \phi_{master} - \frac{2d}{L} \tag{3.4}$$

where d is half the distance between the master and slave wheels.

3.4 User Interface

3.4.1 Physical Interface

Handlebars are used for steering the device in manual mode and indicating an approximate desired direction in assistive mode. They can rotate approximately ± 15 degrees and are spring loaded to return them to the central posi-

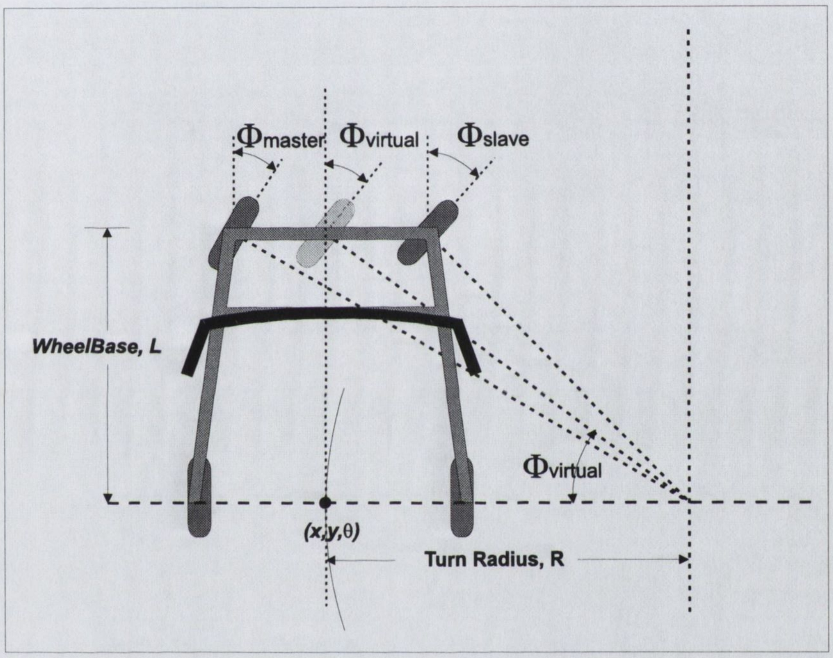


Figure 3.6: Robot Kinematics

tion when no torques are applied. A torque of approximately 8Nm is required to rotate the handlebar to its extrema. The actual steering angle is measured using a hall-effect sensor mounted between two magnets. The hall-effect sensor is mounted on the handlebar stem while the magnets are mounted directly on the frame of the rollator (see Figure 3.7). In the manual mode of operation, the handlebar rotation is converted to a steering angle and the device can be used in the same way as a conventional rollator. In assistive mode the input from the handlebars is sampled to ascertain the user's intended direction (left, right, straight ahead). The two steered wheels are controlled independently because of the high nonlinear relationship between their rotation angles at larger steering angles. It is desirable to achieve these large steering angles for greater manoeuvrability. Rotation on the spot can even be achieved as shown in Fig 3.8. This function is initiated by the user pressing one of the buttons which are mounted on either extremity of the handlebar as shown in the inset. To slow the vehicle down, the wheels are "toed in" by a few degrees from their current alignment. The exact misalignment angle used will depend on the severity of the braking required.

3.4.2 Voice I/O

While many interface designers will only resort to voice feedback in a *busy hands, busy eyes* scenario, the requirements of a potential PAM-AID user dictate the feedback modalities which are of greatest benefit. A number of researchers have attempted to employ voice input for motion control of reha-

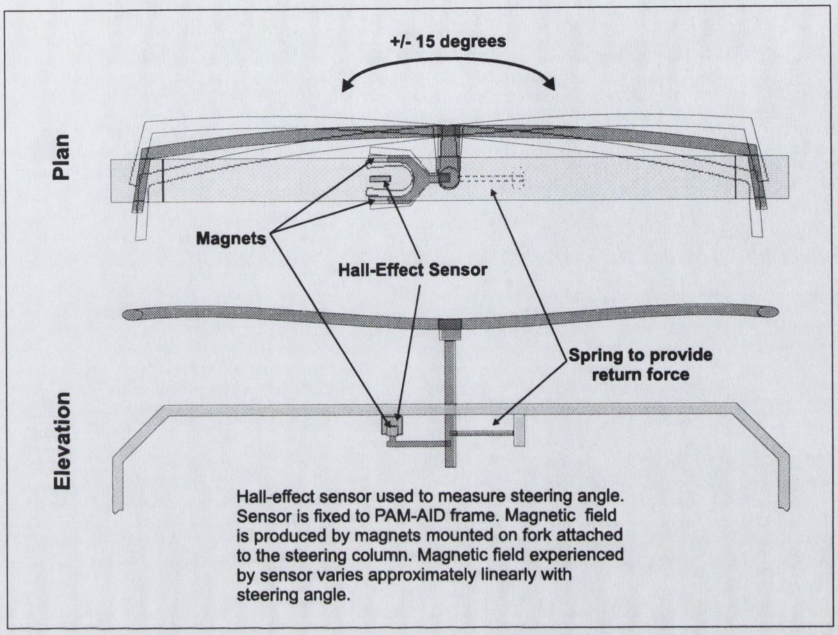


Figure 3.7: Steering Mechanism Details

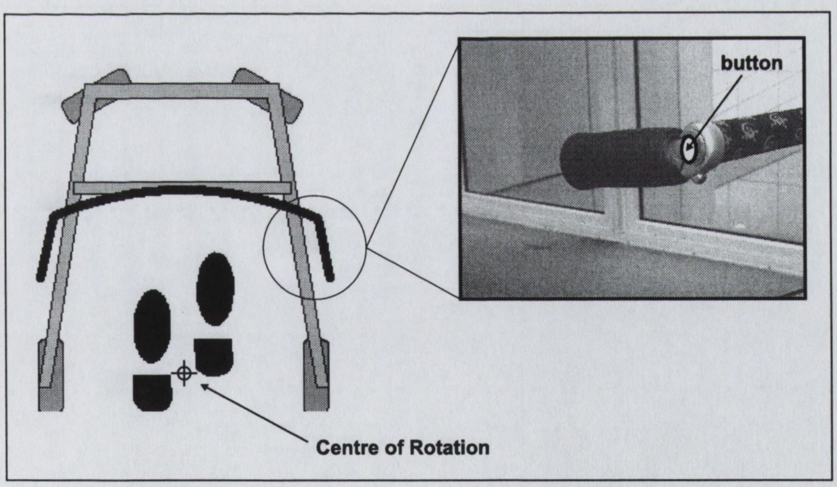


Figure 3.8: User can turn on the spot by pressing button mounted on handlebar extremity as shown in the inset

bilitation robots. All attempts seem to have met with very limited success [26, 97, 52]. Speech, while being very descriptive, is transferred at such a low rate that it is not suitable for motion control. Speech recognition technology is only beginning to tackle continuous speech and is not suitable for the elderly as voice quality and consistency play a huge role in recognition success [52]. Having said that, voice input has the potential to be extremely valuable in assistive technology. The idea of primitive dialogue between the user and the machine could considerably enhance the capabilities of the system as a whole. The passive PAM-AID provided the user with feedback through recorded voice messages. These messages provided three different types of feedback:

- **Commands**: Commanding user to carry out an action e.g. *Forwards, Reverse, Rotate Left, Rotate Right, Stop.*
- **Warnings**: Obstacle proximity warning information e.g. *Obstacle Ahead, Slowly.*
- **Features**: Information on features in the environment e.g. *Opening Left, Opening Right, T-Junction, Dead-end.* Openings are detected using the feature extraction module described in Section 3.9.

Voice is far preferable to isolated tones as people tend to confuse the meaning of more than about three tones. Tonal feedback has been used quite frequently in assistive devices for the visually impaired. It has the potential of being a powerful method for providing continuous feedback on the proximity to obstacles. Heyes in [42] uses the progression of a musical scale to provide the user with absolute distance information. While effective, it requires the user to concentrate on the progression of tones. Continuous feedback has also the disadvantage of masking the user's ability to perceive other sources of auditory cues.

3.5 Hardware

Device control and sensing is distributed through a number of separate hardware modules - an embedded PC, a motion controller and sensor hardware.

3.5.1 Main Controller

The main controller was built around an emdedded PC (Ampro LittleBoard P5i, 233MHz Intel processor). This is a highly integrated single board PC. It is PC-104 Plus compatible and includes a soundcard for the provision of speech and tonal feedback to the user. The hard-drive was shock mounted for added robustness. The PC communicates with the motion controller, the sonar module and the scanning laser rangefinder via serial lines. An functional diagram of the PAM-AID hardware is provided in Figure 3.9.

3.5.2 Motor Controller

The motion control module is custom built around a singleboard micro-controller (Motorola MC68332). The control loop for the steered wheels is shown in Fig 3.10. The motion controller board also handles general I/O. This includes

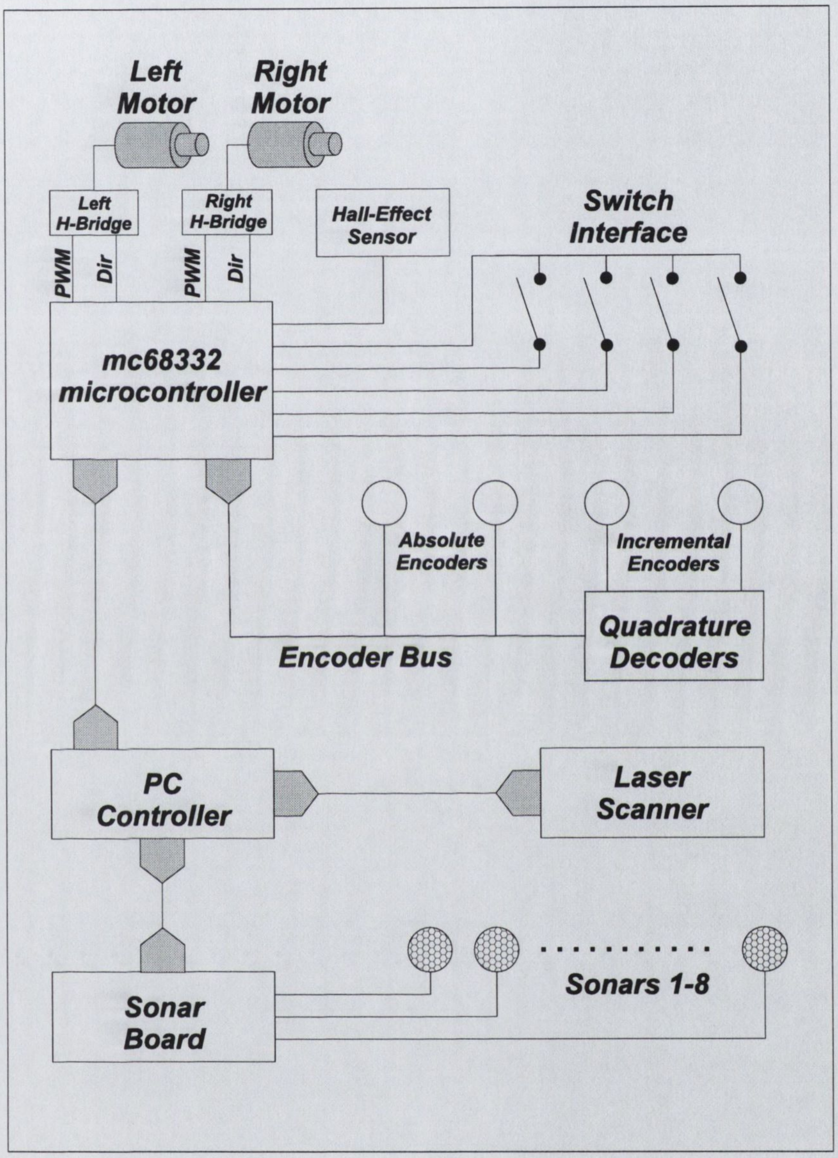


Figure 3.9: Functional Diagram of PAM-AID Prototype Hardware

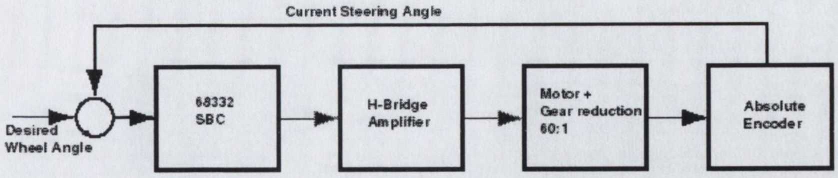


Figure 3.10: Motion Control Feedback Loop

the switch interface and the analog interface for the hall-effect sensor which is used to measure steering angle. All encoders are connected to a serial encoder bus[2] as shown in Figure 3.9. Optical absolute encoders are used for monitoring the steering angles of the two front wheels. Odometric data is acquired using a pair of incremental encoders mounted on the rear wheels of the robot. Aside from steering, the controller is also responsible for maintaining the robot position and heading. In assistive mode, the PC will typically request that the robot servo to a particular heading θ, using a turn radius R. In manual mode, a linear transfer function is used to convert the handlebar deflection angle into a steering angle. This transfer function is currently velocity independent.

3.6 Software

Due to the high demands on reliability, the mobility aid uses the Linux operating system. Its extensive configurability means also that it possible to tailor the system to the requirements of the application. The Task Control Architecture (TCA) [94] was used as a framework for the software design. TCA is

[2]SEI Bus, USDigital Inc., Vancouver, WA

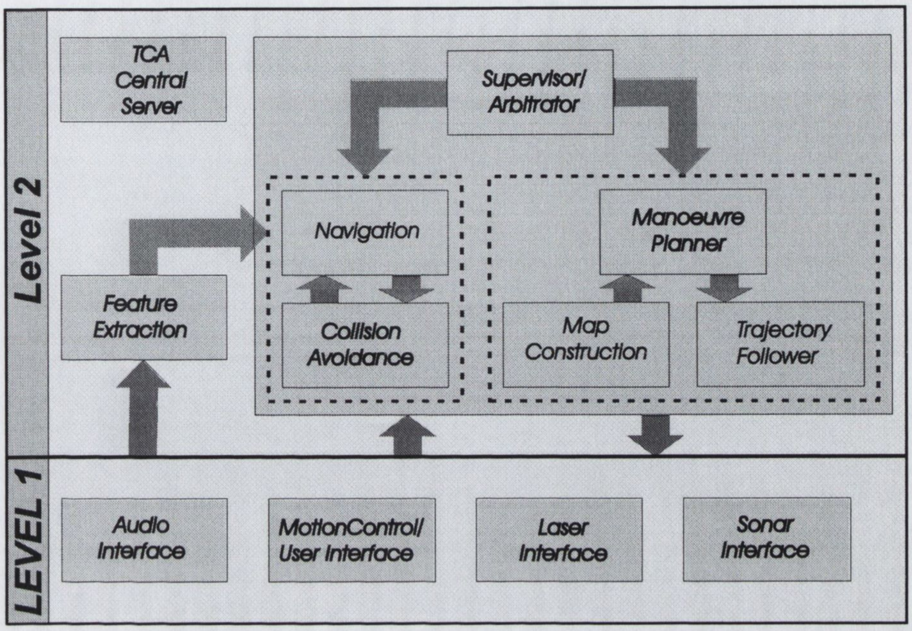


Figure 3.11: Software Architecture

essentially an operating system for task-level robot control. The control can be transparently distributed across multiple machines as TCA can handle all the interprocess communication. A central server is used to pass messages between individual software modules. Other services provided include scheduling, resource management and error handling. Communication between modules is via UNIX sockets.

Figure 3.11 shows the main software modules of the system. A layered architecture was chosen with the possibility of adding more layers for tasks which require more processing time which can run simultaneously in the background. The architecture chosen is similar in structure to the 3T architecture of Bonasso and Kortenkamp [11] and the layered architecture of Simmons et al. [96]. This architecture is ideally suited to the mobility aid which has modules operating in different time frames, requiring data of higher abstraction as one moves up the hierarchy. The first level contains all the low level modules such as the sensor interfaces and the motion control. The second level contains the higher level modules such as navigation, manoeuvre planning and feature extraction. These are grouped into five TCA modules - navigation and manoeuvre planning, feature extraction, motion control, the laser interface and finally the sonar interface. The audio feedback module is integrated into the TCA navigation module as it is the only module that produces audio feedback. All processes run on the same processor. If required however, processes can be moved transparently to other networked processors.

3.7 Sensing

The nature of the application means that the PAM-AID cannot roam or explore in order to construct more accurate representations of the world. Thus, the luxury of averaging over sampled data taken from a variety of positions is not possible. Accurate representations of the world need to be obtained almost on a single-shot basis for reliable functioning of the robot. Various sensor configurations were evaluated for their suitability for the PAM-AID.

Initial experiments were carried out with arrays of discrete sonar transponders[3] in various configurations. Progression from the sonar array to a laser

[3]Polaroid Sensor Transducers with the SonaRanger data acquisition board from Helpmate Robotics Inc, Connecticut, USA

scanner [4] was necessary because of the severe limitations of sonar for accurate ranging. Sonar reflectivity is very much a function of the texture of the reflecting surface and can be hard to deal with in real world environments where there is little or no consistency in the object texture.

The final passive PAM-AID demonstrator used the laser scanner as the primary sensor in addition to an array of sonar transducers. Most of the sonars were redundant backup sensors to the laser, except for the two upwards pointing sensors used for detecting head-height obstacles. While sonar was found to be inadequate as the primary sensing modality, it has certain characteristics which make it a very effective complementary sensor when used in combination with the laser scanner. This is especially true for real world environments. The laser scanner provides range data on a 2-dimensional horizontal slice of the user's workspace. This will not provide an accurate representation for objects like tables and chairs found in a typical indoor environment. The upward pointing sonars however can detect table tops and the broad-beam sonars which are secondary to laser will be more likely to receive reflections from railings and highly transparent media such as glass. Thus, using sonar as a sensing modality can be very effective as long as the designer is exploiting their desirable characteristics and not expecting to use them for sub-centimetre accurate fine-motion planning.

The actual sensor configurations used were very much a function of the navigation algorithms and are therefore described thoroughly in Section 3.8.

[4]LMS-200 scanner from Sick AG, Waldkirch, Germany

3.8 Navigation

A number of collision avoidance algorithms were experimented with in an attempt to find the optimal arrangement for the passive PAM-AID. The main emphasis was on safe navigation and smooth motion. The methods used each have an associated sensor configuration which is described along with the navigation algorithm details.

3.8.1 Ruled Based System

Sensor Configuration

The rule-based obstacle avoidance algorithm relied completely on sonar transducers. The laser scanner was not included in this particular experimental system. The sonar configuration was very similar to that used by Nourbakhsh on the robot Dervish [76, 77]. Fig 3.12 shows the exact configuration. The sonar transducers were arranged into groups. There are seven groups of sonars in all. Four sonars point sideways (one group either side, each composed of two sonars) and are used to determine the presence of any adjacent walls. Two groups point approximately straight ahead. One of the groups is at a height of approximately 40cm and contains 3 sonars. The second group contains 2 sonars and is at a height of 25cm and used for detecting obstacles closer to the ground. Two more groups are set at angles of approximately 45 degrees and -45 degrees. The fifth group comprises two sonars at a height of 30cm from the ground and pointing upwards at an angle of approximately 60 degrees.

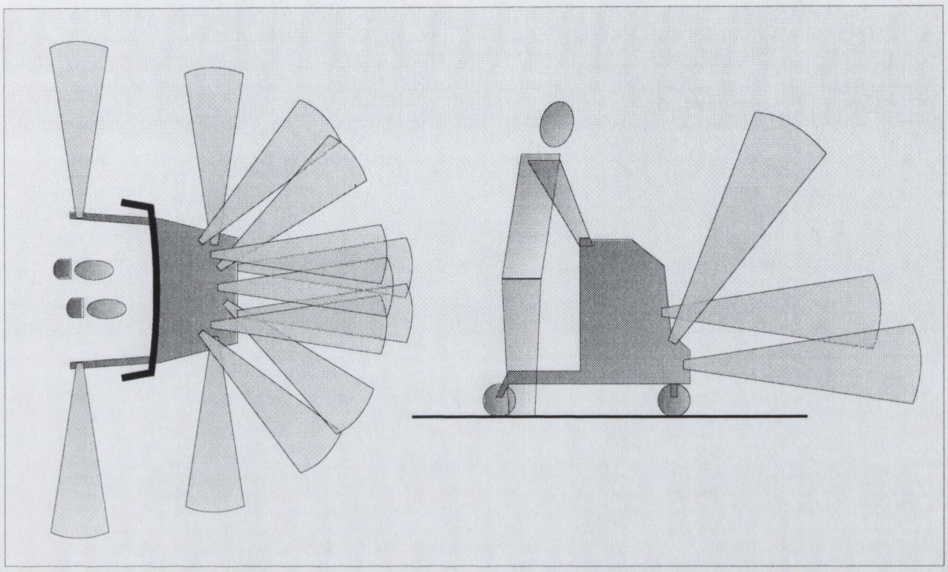


Figure 3.12: Sonar Configuration For Rule-Based System

This group is used predominantly for detecting head-height obstacles and the underside of tables.

The sonar configuration was optimised to detect walls which are parallel to the robot's direction of travel. It was thought that this method would be more reliable than the Vector Field Histogram [12] as the sensor arrangement is optimised for the working environment of the robot. It was thought that the two sonars mounted on either side of the robot would be particularly effective at picking out features in the environment such as junctions and open doors.

Algorithm

The two sonars either side of the robot were used to detect walls. The difference in range readings between the two sensors was used to measure the angle of

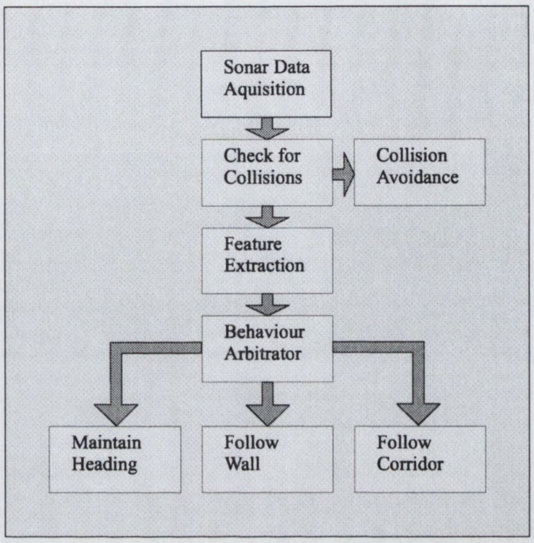


Figure 3.13: Schematic of Rule-Based System

the wall with respect to the robot heading. This was implemented as a look up table. The maximum angle that could be reliably measured was a function of the texture of the surface which was reflecting the sonar pulses. If the surfaces were very smooth, the acceptance angle for returning pulses was very small, typically less than 10 degrees. In contrast, a good textured wall would produce a reliable range reading up to and beyond 30 degrees. The maximum reliable wall angle was set for the robot's current workspace. If the robot returned a wall angle which exceeded this threshold, it was deemed unreliable.

If walls were discovered either side of the robot and they proved to be parallel over a distance of approximately 1 metre, the rollator would servo to the middle of the corridor. A simple proportional control law governed the servoing. The turn radius was lower bounded however, so as not to lose sight of the walls on either side of the rollator due to the limited acceptance angle of the sonars returns. If a single wall were discovered, the rollator would attempt to follow the wall at its current perpendicular distance from it. If there were no recognisable features in the environment, the rollator would maintain its current heading until such time as reliable features were discovered or obstacles were encountered. The rules governing the various wall-following behaviours are presented in Algorithm 1. A simple control law given by

$$\frac{d\theta}{dt} = -\gamma(dist - d_0) \quad (3.5)$$

governs servoing behaviour. Here θ is the steering angle, γ is a gain constant, d_0 is the desired distance from the wall and $dist$ is the current distance from the feature being tracked.

Algorithm 1 Wall Following

```
Proc Wall Following
Begin
if (No Collision Imminent) then
  if (Wall Left and Wall Right) then
    Servo(On Corridor Middle)
  else if (Wall Left and No Wall Right) then
    Servo(On Left Wall)
  else if (No Wall Left and Wall Right) then
    Servo(On Right Wall)
  else if (No Wall Left and No Wall Right) then
    Servo(On Current Heading)
  end if
end if
End
```

The rule based obstacle avoidance routines subsumed the corridor and wall following routines [18]. The control structure is shown in Fig 3.13. For the purposes of obstacle avoidance, the sonars were divided up into logical groups, the most important for obstacle avoidance being the *diagonal_left* group, the *diagonal_right* group and the *forward* group. Tens of cases were compiled which attempted to cover all the typical scenarios the robot would be exposed to. Cases were arranged in a hierarchical way. A typical case consisted of range thresholds for a certain set of sonars and associated conditions. These conditions compared actual range readings with their respective range thresholds. If these conditions evaluated as *true*, an associated motion command was executed, otherwise the next case in the hierarchy was evaluated. The hierarchy structure is such that cases associated with high risk are evaluated first. An example of such a case would be an obstacle at torso height. An outline of the types of cases used is presented in Algorithm 2.

Feature Extraction with Sonar

The feature extraction module uses the sonar returns to determine simple features in the indoor environment such as corridors, junctions and dead ends. The four sideways-pointing sonar transducers are predominantly used for this feature extraction. Evidences for the existence of walls on either side of the device is accumulated. A histogram representation of feature evidences is used. If a particular feature is detected from one set of sonar returns, its evidence is incremented by one, otherwise its evidence is decremented. The feature with the highest histogram score is then the most probable feature in the local environment. For instance, the criteria for a positive corridor identification is that evidence of a wall either side of device is strong and that the measured

Algorithm 2 Rule-Based Obstacle Avoidance

```
Proc ObstacleAvoidance
Begin
GetUserInput()
case:1 //Check for obstacles at torso height
if (HeadHeightObstacle is True) then
  Stop(Alert User)
end if
case: 2 //Check forward group of three sonar
if (All Forward Sonar < Threshold) then
  if ((FreeSpaceLeft is True) and (User Intent is Left)) then
    Servo(TightLeft)
  else if ((FreeSpaceRight is True) and (User Intent is Right)) then
    Servo(TightRight)
  else
    Stop(Alert User)
  end if
end if
.
.
case: n
...
End
```

angles to the left and right walls are parallel within a certain tolerance. Once a positive feature has been identified, the robot will switch into the mode associated with that feature. For example, if the device detects that it is in a corridor, the *follow_corridor* mode will steer the device to the centre of the corridor. Similarly, if a left junction has been detected, the device will query the user on how to proceed.

Performance

The main advantage of the rule-based system over potential field methods is the transparency with which the navigation parameters may be hand-tuned. This applies as long as the number of discrete cases is maintained below a certain threshold ($\lesssim 20$). Tuning then becomes overly time-consuming. The performance of the the robot is noticeably affected by the lack of averaging over consecutive sonar returns. Spurious sonar readings can lead to sudden changes in direction which may in turn alarm the user. This behaviour might not be of concern in a general research robot but makes its application to a human-machine system untenable. Averaging over consecutive sonar readings requires some form of sensor state to be maintained. An occupancy grid [31] is a very efficient method of doing this. It does require, however, a different sensor arrangement than the one presented here (this is discussed in the next section). Despite this tendency of the system to over-react to sensor noise, it performed reasonably well in the *Corridor* environment it was designed for. Results of user studies carried out in Sweden on this system are described in Chapter 6.

The major drawback of the feature extraction module was the time taken to make a reasonably reliable evaluation of the predominant feature in the local environment. It was often the case that the user had already passed the feature of interest by the time the device notified the user by executing a voice message. Also with the presence of specular reflections, the feature extractor would often incorrectly classify a wall as an opening. The combined effects of late classifications and false classifications meant that the system tended to confuse, rather than assist, the user.

3.8.2 Vector Field Histogram with Sonar

Sensor Configuration

The main shortcoming of the rule-based obstacle avoidance was the lack of averaging over many sonar returns to produce a more reliable local map of the environment. Consequently, the sonar configuration was changed such that sonars formed a semicircular ring at the front of the robot as shown in Fig 3.14. Full coverage was required as it made the population of the histogram grid described in the next section much easier.

Algorithm

A reliable local map is very important for smooth motion. Thus, an occupancy-grid map was constructed and updated with each set of new sonar returns. From the occupancy grid, a polar histogram was constructed as described by Borenstein in [12]. This was subsequently thresholded to produce a number

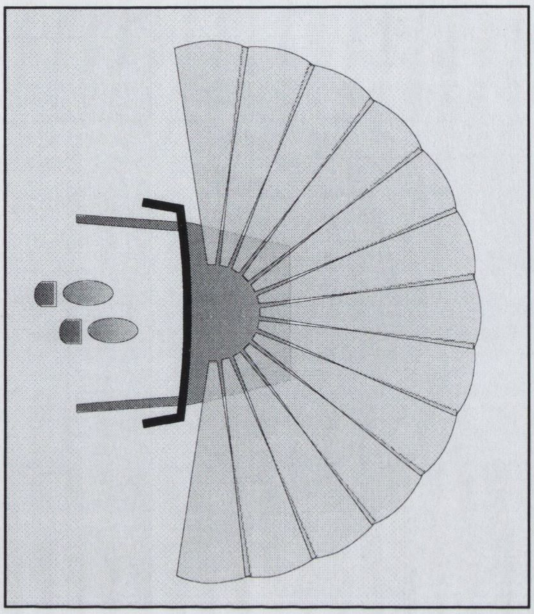


Figure 3.14: Sonar Configuration for Vector Field Histogram

of potential gaps which were safe for the robot to pursue. The robot would servo to the heading associated with the gap closest to the desired direction of motion as indicated by the user. This method dramatically improved the smoothness of motion. Reliable motion, however, was only observed where the wall texture was fairly rough resulting in reliable sonar returns. When smooth surfaces such as doors were encountered, the sonar would reflect off them in a specular fashion giving the impression that free space existed in that particular direction. An example of this undesirable behaviour can be seen in Fig 3.15. The circle represents the threshold for deciding whether a gap is valid for passage. The rollator is in a straight corridor with a closed door on its right. As can be seen from the polar histogram, the closed door

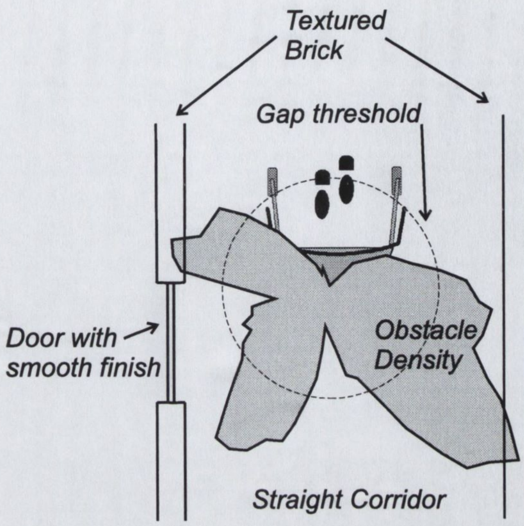


Figure 3.15: False Gap Detected in Polar Histogram as a Result of Specular Reflections

looks like a valid gap. As the rollator approaches the door, the gap disappears but only after the rollator has veered towards it. It thus has to recover from its erroneous decision rapidly. The motion which results is far from smooth.

3.8.3 Potential Field Approach with Laser

The problems of sonar resulted in it being abandoned in favour of a scanning laser rangefinder. The laser range data was found to be far more accurate and reliable. Although potential field methods can be difficult to tune, they make no assumptions about the structure of the environment. This was not the case for the rule-based system described above. The original VFH algorithm described briefly in the previous section does not explicitly take the size of the robot into account. This can result in the robot cutting corners. Such behaviour is not acceptable from a robot designed for visually impaired people. Thus, the VFH+ algorithm described in [14] which *does* take the robot dimensions explicitly into account was adapted for use on the PAM-AID.

The overall algorithm can be broken up into four discrete stages. The algorithm uses a C-space representation of the environment i.e. the robot is represented as a point by enlarging the obstacles in the workspace [66]. A potential field is then constructed using this representation. A threshold is applied to the potential field to produce gaps which are safe for an omnidirectional robot to travel. The user input is sampled and this combined with available gaps is used to calculate a goal heading. Finally, an optimum turn radius is calculated to achieve the goal heading. These steps will be outlined in greater detail below.

C-space

It is essential that the dimensions of the robot are taken into account for robustness of the collision avoidance behaviour. This is achieved by converting the local map returned by the laser into C-space where the robot is converted to a point by enlarging obstacles in the map. How this is achieved can be seen in Fig 3.16.

For this procedure, it is assumed that robot is approximately circular with a radius of 390mm. The distance to the surface of an object is reduced by R where

$$R = R_{robot} + d_{clearance} \tag{3.6}$$

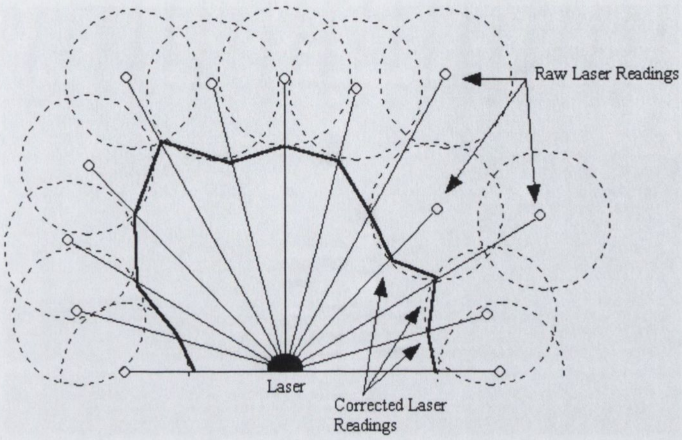


Figure 3.16: Conversion to C-space

where R_{robot} is the radius of the robot and $d_{clearance}$ is the minimum distance to be maintained between the robot and the nearest object. $d_{clearance}$ was set to 100mm.

Potential Field

Following conversion of the local map into C-space, a potential field [49] was constructed using the following formula:

$$PotentialField[i] = \frac{A}{B \times LaserData[i]^2 + 1} \tag{3.7}$$

For the current implementation, A has a value of 2000 and B has a value of 0.000001. Low values of the potential field indicate low obstacle density in that particular direction. The potential field is thresholded to remove gaps which are too narrow for the robot to negotiate successfully. Gaps are further characterised as narrow or wide. For narrow gaps, the heading of the rollator must approximately correspond with the centre of the gap. For wide gaps, the heading of the robot can be any value between the gap walls. Once the gaps have been located and characterised, a gap heading must be followed - this depends on the intentions of the user.

User Input

The user's intentions need to be queried before any new heading is adopted. The feature extraction module developed by Lacey [70, 52] informs the user of any features in the environment which require a decision to be made on the part of the user. Typical features that would require user input would include any sort of junction that would require a choice of direction. A brief description of the feature extraction module is described in Section 3.9. Once the user has been queried on a preferred direction, he can indicate his preference via the user interface. Currently, the user input is broken up into three regions - *left*, *straight ahead* and *right*. This user input is used to influence the choice of direction.

$$\begin{matrix} NEW \\ HEADING \end{matrix} = \begin{cases} HEADING - 60^\circ & \text{if user indicates left} \\ HEADING + 60^\circ & \text{if user indicates right} \\ HEADING & \text{if user indicates straight ahead} \end{cases} \tag{3.8}$$

The gaps which result from thresholding the potential field are ranked according to proximity to the *DESIRED_HEADING*. For wide gaps, each wall

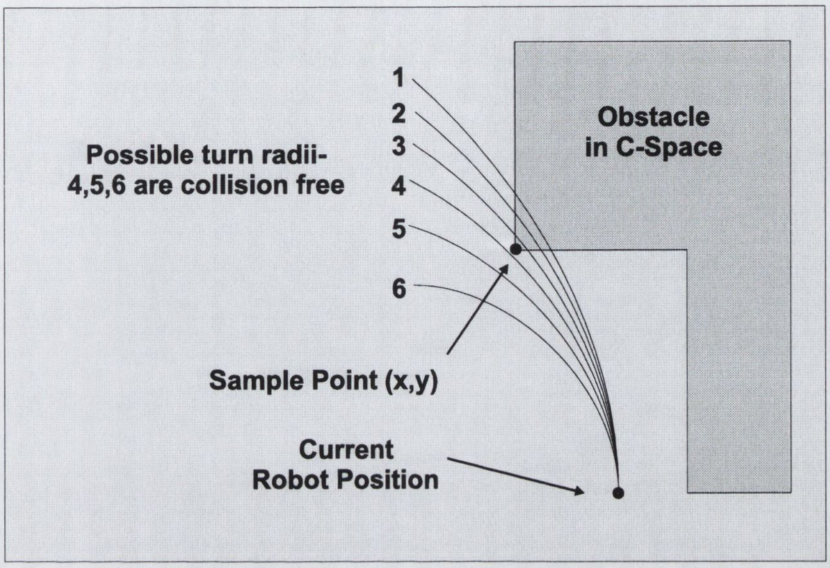


Figure 3.17: Determination of Appropriate Turn Radius

of the gap is treated separately as a contender for being closest to the *DESIRED_HEADING*. This facilitates, for instance, wall following where only one wall exists in the the local environment. The rollator will travel as close to that wall as is safe. If the current heading of the rollator corresponds to an angle within a wide gap and the user's desired direction is straight ahead then no direction alteration needs to be made. For narrow gaps, the midpoint of the gap is chosen as a possible contender for the goal heading.

The rollator has a finite turn radius. The available gaps are all accessible for a device that has a minimum turn radius of zero. A vehicle with this capability can turn on the spot until the desired heading is achieved and then travel forwards in a straight line. The rollator, however, has in normal operation, a minimum turn radius of approximately 550mm. Thus, it may not be possible to reach a particular gap given this kinematic constraint. Once a gap corresponding to a new heading has been chosen, an attempt is made to chose an appropriate turn radius while not colliding with any nearby obstacles. To achieve this, all the points in C-space (which represent returns from obstacles) between the current heading and the desired rollator heading are examined to see if they come within the circle defined by the proposed turn radius. See Fig 3.17. If there is a collision evident then a smaller turn radius is chosen and the procedure is repeated. If no turn radius produces a collision free path, that particular nearest gap is abandoned for the next nearest gap.

The navigation algorithm was tuned for safety rather than speed. The robot will however navigate safely in corridors at over one metre per second and can negotiate a T-junction like the one shown in Figure 3.18 at over 0.6m per second. Needless to say, this is much faster than a typical user can walk (0.3m per second) but provides a large margin of safety for the user. In real terms, the efficiency with which users will progress depends on how they interact with the voice feedback from the robot.

3.9 Feature Extraction

The feature extraction module is used for distinguishing between different corridor types. It was developed by Lacey [51] and one of its main strengths is its noise immunity. A diagram showing the range of corridor types the system is able to recognise is shown in Figure 3.19. A short description of the module is included here for completeness as it accounts for much of the higher level

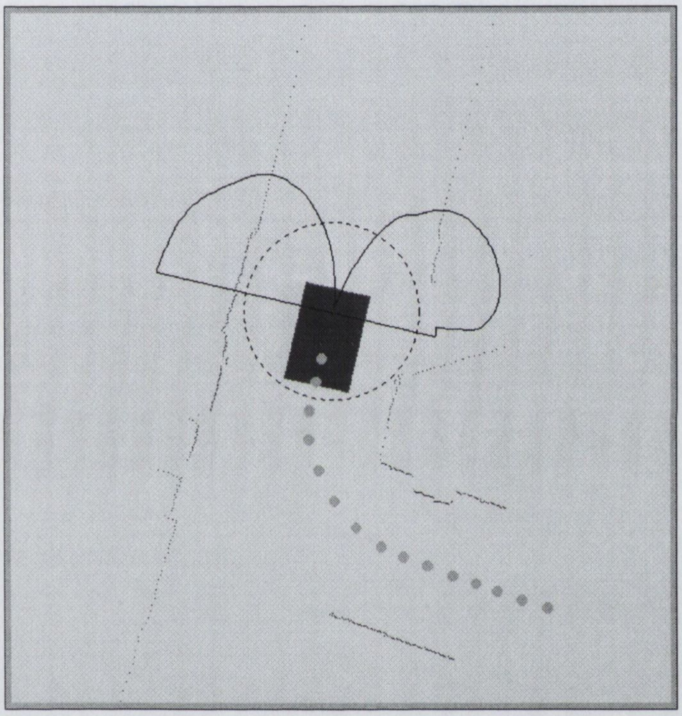


Figure 3.18: The Robot Negotiates Junction at Over $0.6m/sec$

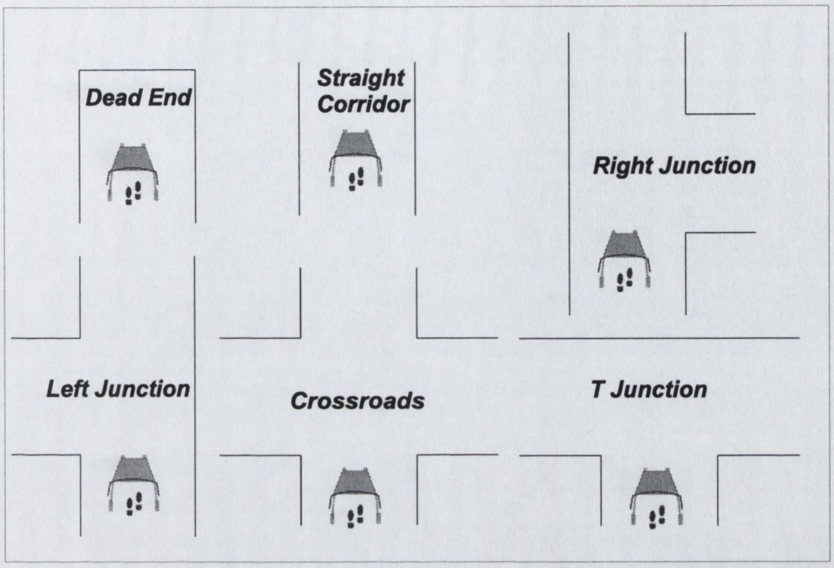


Figure 3.19: Corridor Types

feedback provided to the user.

The corridor types were recognized from the laser data. The straight line features were extracted from the range scan using the Range Weighted Hough transform [36]. The position, length and angle of the features were input into a Bayesian Network [83] in order to classify the types of corridors present. The structure of the corridor classification network is shown in Figure 3.20.

The network contained three layers of nodes. The lowest layer represented the raw feature evidence. Feature strength was proportional to feature length and scaled as being one of the set $\{weak, medium, strong, certain\}$. This classification represented the size and type of line features around the robot. The middle layer of nodes represented the likelihood of each feature given the uncertain sensor input and as such represented the error in the sensor/feature detection system. The top-most layer of the network classified the features into one of the six corridor types. The prior probabilities in the Bayesian Network were trained using example laser scans and a learning algorithm. The laser scans were taken from a variety of different positions to ensure robustness and generalization. The learning algorithm incremented a feature's causal probability when it supported the corridor classification and reduced it otherwise. After training, the bias in the training data was apparent due to the lack of symmetry in the network and the over-sensitivity of some corridor classifications. Shannon's measure of Mutual Information [91] and entropy reduction were used to identify the nodes contributing to this over-sensitivity and guided the tuning of the network. The corridor classification was passed to the user interface system where a recorded voice message would provide the user with a description of the environment.

The bayesian network has very high reliability on the features it has been trained on. It will recognize features at a distance of between 50 and 80cm. A typical user would travel at about 30cm per second. Thus, they have approximately two seconds to make a decision on the direction they want to take. This makes for fluent motion on the part of the user.

3.10 Summary

This chapter explored the motivation for choosing a passive robot over an active robot. Various different possibilities for highly manoeuvrable drive

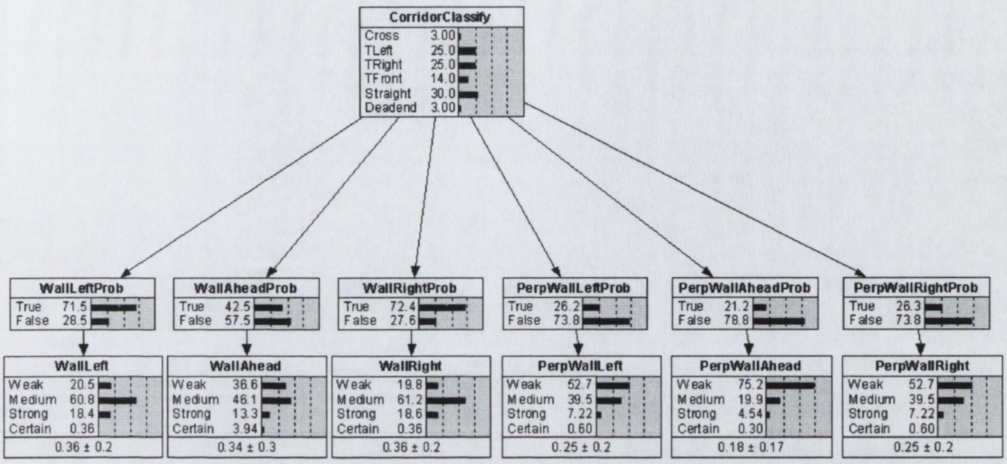


Figure 3.20: Bayesian Network used for feature selection

modules suitable for indoor use were discussed and the final mechanical design was described in detail. The final hardware and software architectures were presented. A variety of different sensor configurations and navigation algorithms were evaluated. Despite the fact that only the final of the three navigation/sensing combinations really met user requirements, all combinations were described to provide background for the usability trials described in Chapter 6.

Chapter 4

Planning with Uncertainty

4.1 Overview

This chapter discusses a cooperative strategy for negotiating situations where the robot cannot navigate autonomously. Specifically, it addresses situations where a manoeuvre is required to escape from a dead-end/local minimum[1] in the workspace. The robot needs to work together with the user to execute such a manoeuvre. The chapter opens with a discussion of the constraints imposed on the system by both its non-holonomic and passive nature. This is followed by a discussion of the map building process, the collision detection algorithm and finally, the manoeuvre planner itself. The planner takes into account the uncertainty in positioning which results from the user having a large influence on the dynamic behaviour of the system.

[1]The term local minimum is used in the context of descending a potential gradient. A local minimum occurs when gradient decent is no longer possible. This term is used as the PAM-AID navigation algorithm uses a potential field approach.

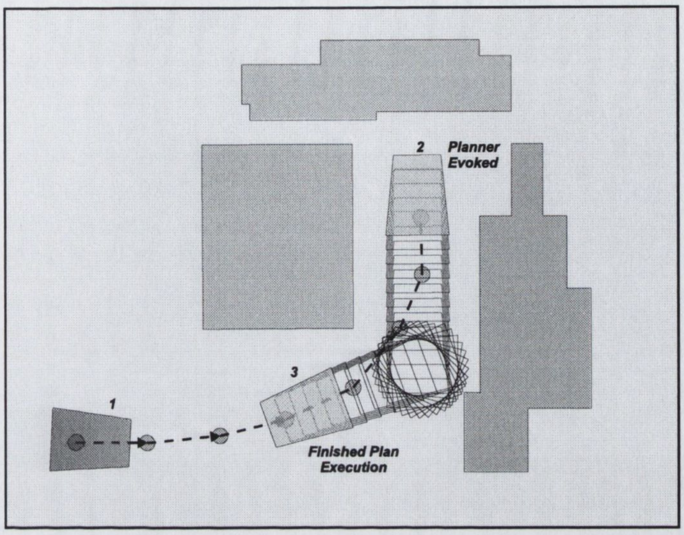


Figure 4.1: Trajectory followed on cooperative manoeuvre out of local minimum

4.2 The Manoeuvre Planner

The human-machine system which is the focus of this work is non-holonomic. It cannot move tangentially to its current direction of motion unless it is stopped and the rotate-on-the-spot function is used (see Section 3.4). Further, because of its elongated shape, it cannot be accurately represented by a bounded sphere. There are additional constraints imposed on the system by the specific requirements of the user. Visually impaired people are discouraged from walking backwards so any planning algorithm incorporated into the system must try to minimize the amount of reversing required of the user. Additionally a planned manoeuvre takes the order of a second to compute. Longer computation times would not be tolerated by the user.

Considering all the constraints imposed on the system, it was decided to focus on a small class of manoeuvres which would be useful to a user in a variety of situations such as coping with dead-ends, undocking from tables and changing direction in cluttered environments. The nature of the manoeuvre is a straight reversal (if necessary) followed by a rotation on the spot. Figure 4.1 shows a typical situation where the planner is required. The user has ended up in a situation in which the general navigation routine has failed (position 2). The goal of the planner is to find a path such that the user ends up on the trajectory that was already followed, but facing the opposite direction(position 3). The PAM-AID is mechanically, a passive device. Such a manoeuvre requires the robot and the user to operate in a cooperative manner.

It was decided not to use brakes on the PAM-AID except when the system deemed it absolutely necessary (e.g. descending a ramp). It was felt that constant braking by the robot would be frustrating to the user. Thus, the user has complete control over the speed and direction of the robot but is guided by verbal cues. Typical commands include *Reverse*, *Rotate Left*, *Rotate Right* and *Stop*. The planner must take into account the uncertainty in positioning which ensues from the user having such a huge influence on the dynamics of the system. It is not sufficient for the planner to plan a single path. A whole suite of possible paths must be planned to take the uncertainty of user behaviour into account. A dynamic model of the user is essential in order to put a bound on the uncertainty.

The planner is evoked by the user when the collision avoidance algorithm cannot return a free path for safe navigation. It subsequently tries to find a path out of a local minimum. An accurate representation of the robot's local workspace is very important if the planner is to yield successful results. This is very much a function of the quality of the sensor data. Also required is a collision detection algorithm which is optimized for the type of objects characteristic of the robot's workspace. These issues are discussed in detail in the following sections.

4.2.1 Map building

The whole planning and execution procedure cannot begin without an accurate representation of the environment. The PAM-AID does not maintain a global map of its work environment, it does however maintain a history of its pose (position in cartesian space and heading) along with the range data from the laser scan sampled at that particular robot pose. This history extends for approximately four metres (or approximately ten laser scans). If the planner is evoked, the laser scans are compiled together to produce a coherent map of the local environment. Where a number of scans cover the same region in space, the newest scan (or portion thereof) is used to represent this region. This is illustrated in Figure 4.2. The odometry error is small (5cm over 4m, 4° over 360°) and as a result does not warrant the use of techniques such as Kalman Filtering [62, 56] or global scan alignment [67] to fuse scans together. These methods are computationally expensive and are really only necessary in the maintenance of global maps.

Algorithm

Algorithm 3 Fusion of Laser Scans

---

for all ($points \in scan[1]$) **do**
  $localMap \leftarrow point$ //include all points of current scan
end for
//n is the scan number
for (i = 2 to n) **do**
  for all $points \in scan[i]$ **do**
    if ($point\ behind\ baseline[i-1]$) **then**
      $localMap \leftarrow point$
    end if
  end for
end for

The laser range data consists of 181 range values covering 180 degrees. The range data from the stored scans is converted from polar into cartesian coordinates and transformed into the current reference frame (the reference frame moves with the robot, i.e. the map is egocentric). A line is also associated with each scan — the *scan baseline.* This line cuts through the laser source and is perpendicular to the heading of the robot when the scan was acquired. These baselines dictate which points of a particular scan are kept and which are dropped. An outline of the method is given in Algorithm 3. Consider, for instance, the n^{th} scan. Points belonging to the n^{th} scan are by default in front of the n^{th} scan baseline[2]. All points of the n^{th} scan which are in turn behind the $n-1^{th}$ scan baseline are kept. Those in front of the $n-1^{th}$ baseline are rejected as points from the $n-1^{th}$ scan cover this region. Accepting and rejecting points is quite efficient. If the baseline is represented

[2]Scans are numbered in ascending order starting with the most recently acquired scan

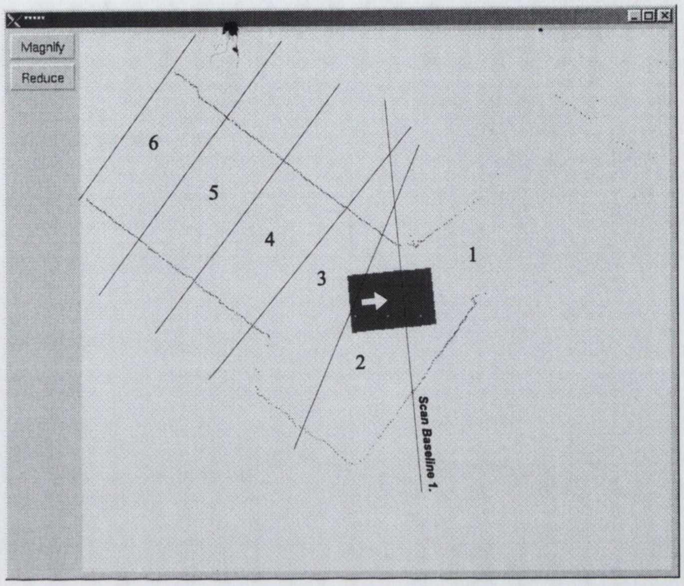


Figure 4.2: Construction of Local Map. The Numbers Denotes Scan Origin.

by the line

$$ax + by + c = 0 \tag{4.1}$$

A point (x_{front}, y_{front}) from in front of the scan baseline when substituted into the above equation will yield a result of opposite polarity to a point (x_{back}, y_{back}), from behind the baseline. Thus a scan point can be accepted or rejected based on its substitution in the above equation which consists of just two multiplications and two additions. This method is attractive as the number of data points is reduced to a minimum while coverage is not sacrificed. Also, the data points which are retained are the most accurate points representing that region without having to employ expensive estimation techniques.

4.2.2 Collision Detection

A highly structured environment (e.g. a corridor setting) would allow for the raw map data to be distilled into a set of line segments using for instance a *Hough transform* [36, 3]. This would then allow for highly efficient collision detection which is normally the bottleneck in the planning process. The environments which the PAM-AID is exposed to can vary greatly in structure from the corridor type environments (like in Figure 4.2) to more challenging environments (see Figure 6.4) containing features which cannot simply be described by straight lines.

The raw representation of the environment produced by fusing scans was not suitable by itself for collision detection. To achieve a more compact representation of the data, an occupancy grid [31] was thrown over map. The occupancy grid consisted of (200×200) cells with a cell length of 25mm. Cells containing map points were filled, empty cells remained empty. Adjacent filled cells are grouped together in a segmentation process (blob detection). This was achieved by a rasterized scan of the grid. Regions were grown by looking for 1-neighbours and 2-neighbours [88]. The data was then in a suitable format for the collision detection algorithm.

There are many techniques for efficient collision detection. The most appropriate method for an application depends to an extent on the object shapes that one is dealing with. Some methods such as I-Collide [23] require that the objects be convex. Most algorithms use some form of bounding volume. Quinlan [86], for instance, uses bounded spheres. The use of bounded

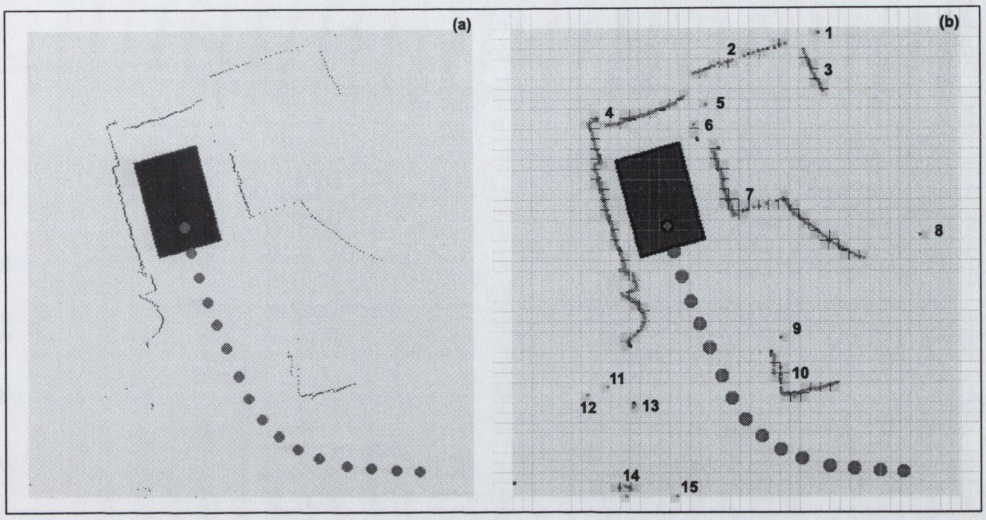


Figure 4.3: (a) Raw scan data (b) Occupancy grid thrown over scan data. The segmentation process produces 15 separate objects

spheres is very efficient for the representation of compact objects which have similar length, width and breadth dimensions. Others, such as OBBTree [38], which is based on oriented bounded boxes, work better with more elongated shapes. This method derives from Ballard's work [5] on strip trees which were used for the hierarchical representation curves. Bounded volumes by themselves only work with convex shapes. To extend the method to concave and articulated bodies, a hierarchical structure of bounded volumes is required. OBBTree makes use of this hierarchical structure. For a more detailed description of collision detection refer to [64].

The environment that the robot was exposed to was reasonably heterogeneous in the size and shape of objects but there was a predominance of elongated objects while the robot was in the corridor environment. Thus, RAPID[3], an implementation of the OBBTree algorithm, was used. RAPID works with polygonal models which do not require any topological structure. In this application the *blobs* which result from segmenting the occupancy grid are converted to polygonal models (the occupancy grid cells which are memebers of a *blob* are converted to triangles — two triangles per cell). RAPID takes as input, two models along with their position and orientation in cartesian space. It returns a list of the contact triangle pairs. RAPID unfortunately does not provide any information on the proximity of two objects. What might be of interest for further work is to use a method such as PQP [55] which builds on RAPID and also provides distance information which then could be reconciled with sensor uncertainty.

4.2.3 Planner Detail

The planned manoeuvre was composed of a *straight reversal* followed by an *on-the-spot rotation*, followed by the user pushing the PAM-AID *forwards.* If a reversal was not necessary then the manoeuvre consisted of an on-the-spot rotation followed by a forward motion. The manoeuvre had to be kept relatively simple because of the constraints imposed by user group for which the system was designed. The reverse motion was restricted to a straight reverse for two reasons. Firstly, users found it difficult to simultaneously reverse and turn. Secondly, adding curves to the trajectory would increase the search space

[3]RAPID — **R**apid and **A**ccurate **P**olygon **I**nterference **D**etection. Developed by the Research Group on Modeling, Physically-Based Simulation and Applications, University of North Carolina. http://www.cs.unc.edu/ geom/OBB/OBBT.html

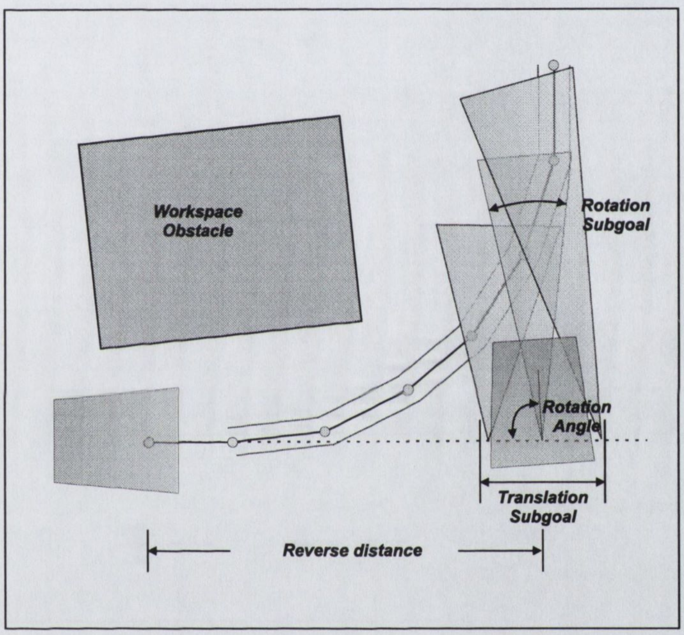


Figure 4.4: Trajectory followed on cooperative manoeuvre out of local minimum

and thus the time taken to find a set of solutions. As the planner calculates a plan on request, it has to return a solution in a matter of seconds. This would be possible if the uncertainty associated with the dynamic behaviour of the human-machine system were negligible. This is however not the case and consequently, the planner must calculate a suite of possible trajectories in order to ensure goal reachability.

Goal Definition

Before any planning could take place, a goal which was both reachable and recognizable had to be defined. The goal for the manoeuvre was to join up with the path followed by the robot prior to the robot's current pose while facing in the opposite direction. It is reasonable to assume that this is a free path as the robot has already traversed it. This considerably reduced the search space for finding a suitable manoeuvre and ensured that a path would be returned in real-time if a path existed. The goal was represented by a set of finite length vectors which approximated the path. This is illustrated in Figure 4.4. A manoeuvre plan was defined as successful if the path which formed the last part of the manoeuvre (the forward motion which followed a rotation-on-the-spot) intersected with a vector of the goal set. The angle between this proposed path and the goal vector had to be below an upper bound. This was set at 45 degrees. This facilitated the robot taking over control and quickly adjusting its steering angle such that the robot heading and the goal vector were roughly parallel. The robot used odometry to monitor its position relative to the stored map and trajectory history. The robot could thus estimate when a manoeuvre was completed.

Dealing with Uncertainty

The planner accounted for the uncertainty in motion control by calculating bounded regions in Cartesian space for which goal achievement was certain[4]. The user would be able to reverse into a region (a translation subgoal), such that for each point in this region, there existed an associated region or regions of feasible rotation angles (rotation subgoals) which encompassed the final manoeuvre goal. These regions are illustrated in Figure 4.4. If the user can rotate to an angle which is between the bounds of a rotation subgoal, goal reachability is guaranteed when the robot is pushed forwards. For clarity, only three rotation regions, each corresponding to a distinct reversal distance, are illustrated. The auxiliary lines either side of the goal trajectory are also goal trajectories. Their function is to slightly dilate the rotation regions when the goal trajectory is very straight. The offset of these lines from the main goal trajectory is set at 10cm. If these lines were absent, the planner could theoretically return a rotation region of only 1 degree in width. The positioning accuracy of the human-machine system cannot meet such a high tolerance. A very narrow rotation region could result if the user had followed a perfectly straight trajectory and was subsequently required to rotate through 180 degrees. The auxiliary lines result in rotation regions with a minimum width of approximately 10°

[4]The term *certain* needs qualification. It is based on the assumption that the user behaves in accordance with the system's dynamic model of him or her

This approach to planning with uncertainty is similar to the preimage backchaining approach of Lozano-Perez described in Section 2.4.3 where intermediate goals are also defined. Instead of back-chaining, however, motion commands are forward-chained to reach the goal. Once a reasonable model for user behaviour exists, then it should be possible to provide the appropriate feedback which would ensure that the user moves the robot to within the intermediate goal and final goal bounds. The preimage concept associated a terminating condition with each motion command which ensured that the robot halted within the goal region. For the manoeuvre planner described here, the aim is to stop the robot in the middle of a subgoal region[5]. To achieve this, the robot must be able to predict when the user must be commanded to stop. The stopping distance is velocity dependent. During each control cycle, the velocity is sampled and the stopping distance estimated. If the distance to the subgoal target is less than or equal to the stopping distance, the terminating condition is triggered and the user is commanded to stop. This will be described in more detail in Chapter 5.

Many planning algorithms represent the robot as a point object in Configuration Space (C-space) [66]. This is advantageous if the workspace is static and a number of plans have to be calculated. For this particular application, a map is constructed on the fly for the current situation and is then discarded after the trajectory execution algorithm has returned successfully. Converting the entire map to a C-space representation was deemed an unnecessary

[5]If the subgoal is large, the target within the subgoal region will be moved to minimize a reversal or rotation

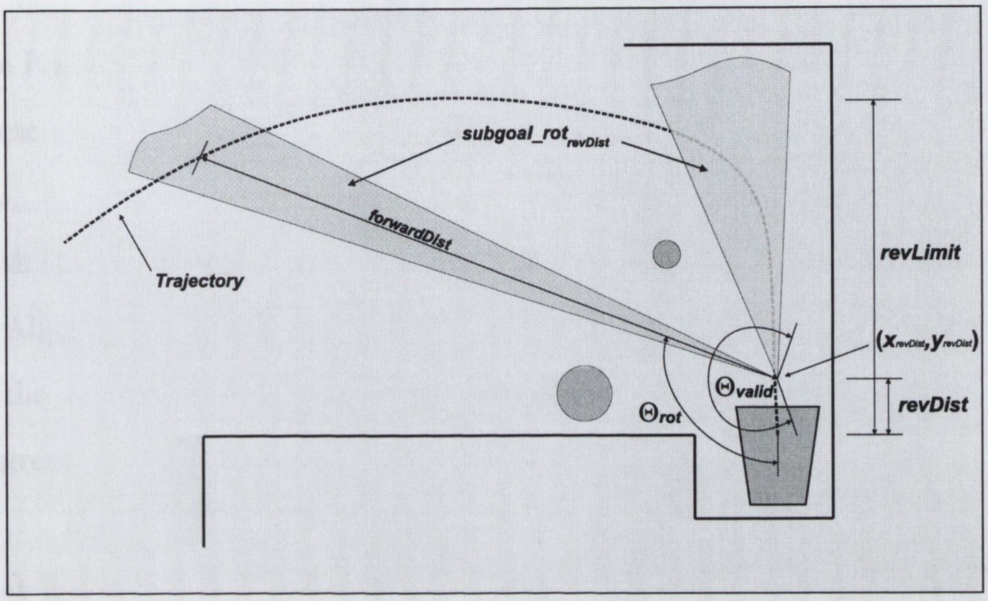


Figure 4.5: Illustration of Algorithm Details

processing step.

Algorithm

The algorithm described here calculates the translation and rotation subgoal regions for a manoeuvre. Examples of such subgoal regions are shown in Figure 4.6. The procedures presented in Algorithms 4 and 5 outline the main aspects of the algorithm. Figure 4.5 illustrates some algorithm parameters. To begin, *revLimit* is calculated. This is the maximum distance the user can reverse without a collision. Then, for each incremental reversal (each value of *revDist* between 0 and *revLimit*), the clockwise and anti-clockwise rotation bounds are calculated (θ_{max_cw} and θ_{max_ccw}). These are defined as the limits for collision free clockwise and anti-clockwise on-the-spot rotation. The set of angles between these bounds is denoted by $\{\theta_{valid}\}$ and is calculated by the function ROT_LIMITS. The robot is then incrementally rotated within these rotation limits. For each rotation step, a line is projected from that point $(x_{revDist}, y_{revDist})$ with a slope of $tan(\theta_{rot})$. This line is tested for intersection with the line segments of the goal trajectory (function $GOAL\_INTERSECT$ in Algorithm 4 and in more detail in Algorithm 5). An intersection is successful if the angle between a goal segment and the projected line is less than 45 degrees.

If the intersection is successful, collision detection is performed along that line. The line length ($forwardDist$) is important. It must be at least of a minimum length, such that on rotation, the front wheels of the robot are not beyond the point of intersection of the projected line and the goal segment. This is to ensure that the robot does not overshoot the goal trajectory. If no collision is detected, the rotation angle along with the direction of rotation and the distance to the goal trajectory are added to the set of valid rotations $\{R_{revDist}\}$ for the reverse distance $revDist$. If rotation in both directions yields a valid result, the shortest angular distance is preferred. The user can thus reverse a distance $revDist$, rotate to angle θ_{rot}, push forward a distance $forwardDist$ and be guaranteed to reach the manoeuvre goal. Once the set of valid rotations for a certain $revDist$ have been calculated, they must be sorted into regions of contiguous angles ($subgoal\_rot_{revDist}$) where each angle guarantees goal reachability for the robot. This is done by the function *ROT_REGIONS*. Figure 4.5 depicts a situation where $\{R_{revDist}\}$ yields

Algorithm 4 $TRANSLATION\_GOAL$

Var T //Set of translations with reachable goal
Var $R_{revDist}$ // Set of rotations with reachable goal
Var $regionSize_{Trans}$ //Translation Goal Width
Begin
$revDist \leftarrow 0$ //Reverse Distance for Manoeuvre
$revLimit \leftarrow TRANSLATION\_LIMIT()$ // max $revDist$ without collision
while $(SIZE(subgoal\_trans) < min)$ & $(revDist < revLimit))$ **do**
  $\theta_{valid} \leftarrow ROT\_LIMITS$ //Collision free rotation angles
  for all $\theta_{rot} \in \{\theta_{valid}\}$ **do**
    $goalIntersect \leftarrow GOAL\_INTERSECT(x_{revDist}, y_{revDist}, \theta_{rot})$
    if $((goalIntersect = true)$ & $(path\ is\ collision\ free))$ **then**
      $T \leftarrow revDist$
    end if
  end for
  if $R_{revDist} \neq \emptyset$ **then**
    $subgoal\_rot_{revDist} \leftarrow ROT\_REGIONS(R_{revDist})$
  end if
  if $T \neq \emptyset$ **then**
    $subgoal\_trans \leftarrow TRANS\_REGIONS(T)$
  end if
  $revDist \leftarrow revDist + revStep$
end while
return($subgoal\_trans$, $\{subgoal\_rot_{revDist}$ for all valid $revDist\}$)
End

Algorithm 5 *GOAL_INTERSECT*

Precondition for valid intersection: Angle between line segments < 45 and length of testSegment $\geq$ wheelbase

```
Var Goal // Set of line segments making up goal trajectory
Begin
success ← false
for all goalSegs ∈ Goal do
  INTERSECTION(x_revDist, y_revDist, θ_rot, goalSeg)
  if (intersection = true) then
    collision ← COLLISION_CHECK() //Check path is collision free
    if (collision = false) then
      R_revDist ← θ_rot
      success ← true
    end if
  end if
end for
return success
End
```

two discrete rotation subgoals. Each value of *revDist* which returns a valid set of rotation angles is added to the set of successful reversals $\{T\}$. When the incrementing of *revDist* is completed, the contiguous values of *revDist* which have valid rotation regions ($subgoal\_rot_{revDist}$) are grouped into regions (*subgoal_trans*). Thus, associated with each element of *subgoal_trans* there exists a $subgoal\_rot_{revDist}$ which guarantees goal reachability.

4.3 Experiments and Discussion

To illustrate the planner in operation, an example is given in Figure 4.6. The planner has generated two discrete translation subgoals which are marked in Figure 4.6a. A reversal into the first translation subgoal should be followed by a rotation to left, whereas a reversal into the second translation subgoal should be followed by a rotation to the right. Figure 4.6b shows the outline of a manoeuvre using the first translation subgoal. Also included is the rotation subgoal. This is real data from a field trial which is described in more detail in Section 6.4.1. The subgoal data generated by the planner is presented in detail in Table 4.1. The first translation subgoal has a width of 400mm while the second is much narrower with a width only 100mm. Columns 2 and 3 tabulate the rotation subgoal extrema. The column labelled *Forward Distance* lists the distance the user needs to move forward following a rotation in order to actually reach the goal. It should be noted from the table that the width of the rotation subgoal is consistently narrow over the whole range of possible reversal distances ($\sim 10°$). A dynamic model of the human-machine system is important for the system to stop in the bounds of this rotation.

One important issue regarding the planner which has not yet been addressed is that of *controllability* — will the manoeuvre planner return a viable path connecting the system's initial configuration, q_{init} with a goal configuration, q_{goal}? The answer is no but it deserves qualification. The criteria which need to be fulfilled for controllability of a non-holonomic vehicle are discussed by Latombe in [58]. He states that any robot that is subject to a single non-singular scalar linear nonholonomic equality constraint is fully controllable. The nonholonomic constraint governing the PAM-AID's kinematic behaviour was given in Equation 3.1 which fulfils the conditions for controllability. What must be emphasized here though is that reaching an arbitrary goal could entail a large number of discrete Reed-Schepp type manoeuvres [87]. A real world example to illustrate this point would be the case of trying to parallel park a car in a parking space marginally longer than the actual car. A large number of iterative forward and reverse motions are required. In the case of the PAM-AID, it cannot be expected of the user to react to the robot's commands to repeatedly reverse and proceed forwards. The use of the *turn-on-the-spot* facility allows the robot to be kinematically modeled as a unicycle and removes much of the manoeuvering associated with a car-like vehicle. Another factor which guarantees the high success rate of the manoeuvre planner is the fact that the general obstacle avoidance routine will set the steering angle to zero if no traversable gap exists in the potential field i.e. the PAM-AID will move in a straight line (Section 3.8.3). Thus, if the manoeuvre planner is called when the GOA (General Obstacle Avoidance) has failed, it is likely that a straight reversal as part of the planned manoeuvre is possible. While the controllability of the PAM-AID under the manoeuvre planner was not explicitly studied, the most important outcome of its implementation was the significant improvement in a user's ability to navigate independently. The usability trials of the planner are discussed in Section 6.4.1.

4.4 Summary

This chapter described a manoeuvre planner, designed to assist the user in escaping from local minima in the environment. The planner was composed of a number of discrete components.

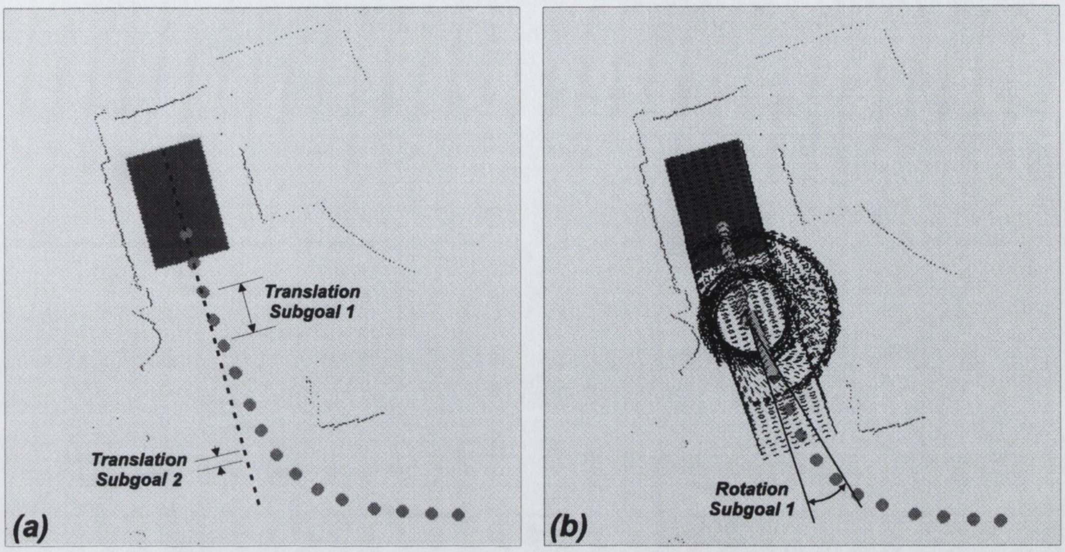


Figure 4.6: Example of cooperative manoeuvre. The subgoal data calculated by the planner is presented in Table 4.1

- *Dynamic map building.* The map was constructed on-the-fly when the user requested help. In this way, the computational overhead of constant map maintenance was avoided.

- *Model representation.* Typical environments were quite heterogeneous. Thus obstacles in the environment were represented using an occupancy grid. The occupancy grid provided an explicit representation of free space. Adjacent occupied cells were grouped together into obstacle models.

- *Collision detection.* Collision Detection was achieved with RAPID. This library was ideally suited to the models produced from the occupancy grid representation of the world.

Reverse Distance (mm)	Rotation Lower Bound (degrees)	Rotation Upper Bound (degrees)	Rotation Direction	Forward Distance (mm)
550	288	300	Right	1458
600	288	299	Right	1317
650	289	300	Right	926
700	290	300	Right	1050
750	291	301	Right	1080
800	291	301	Right	949
850	292	302	Right	951
900	293	303	Right	975
950	294	304	Right	992
1750	325	343	Left	1097
1800	328	344	Left	859
1850	331	346	Left	1097

Table 4.1: Numerical data from manoeuvre plan of Figure 4.6

- *Search.* The manoeuvre planning algorithm searched for regions in free space through which the robot could rotate and translate. The goal of the planner was to find a set of reachable robot configurations such that the general navigation routine could take over control.

The planner might be best described as an *undocking* routine. A user might, for instance, leave the PAM-AID beside a chair or in a corner. When the device is required again, it first needs to be manoeuvred back out into free space. The planner provides a mechanism for this. Once a successful plan has been produced, it is passed to the trajectory execution module. This module endeavors to execute the manoeuvre generated by the planner. The trajectory execution module requires a dynamic model of the human-machine system for successful plan execution. This is described in detail in the next chapter.

Chapter 5

User Modelling and Trajectory Execution

5.1 Overview

Once a successful plan has been produced, it is passed to the trajectory execution module. This module endeavours to execute the manoeuvre generated by the planner. Trajectory execution is dependent both on the path returned by the planner and a dynamic model of system. For an autonomous robot, this dynamic model is normally deterministic and well defined. In the case of the PAM-AID, one has to take into account the dynamics of the whole human-machine system. The user introduces a component of uncertainty into the dynamic modelling process which is not present in traditional robotic systems. The forces applied and characteristic reaction times of users can vary. Any model must be user specific and should ideally *adapt* to the user's behaviour.

5.2 User Model

The passive nature of the PAM-AID means that the user must be prompted by the robot to move. The robot cannot expect that when it issues a voice message, the user will respond instantaneously. This is especially true in the case of elderly people, whose response times can be significantly longer than those of younger people. It is important to take this time delay into account. For example, if the user is moving at 200mm/sec, failure to accommodate for the user's delay in response(~250msec or 5cm at 200mm/sec) could be the difference between following a safe path and colliding with an obstacle in the environment. When analyzed in control theory terms the processing of the voice message (perception and cognition phase) can be modeled as a pure time delay, e^{-st}[1]. Another delay — neuromuscular delay, will also account for some fractions of a second. This is the time between sending a command to the muscle and the time for the muscle to actuate. This will depend on the inertia of the physical system and is normally modeled as being a first order system. An approach like this tends to generate parameters which need to be experimentally determined but can be very difficult to measure. While this approach is necessary in order to gain insight into the functioning of the system, it is not necessarily good for prediction. For the PAM-AID, a more phenomenological approach was adopted which produced easily measurable

[1] This is actually the Laplace transform of the time delay.

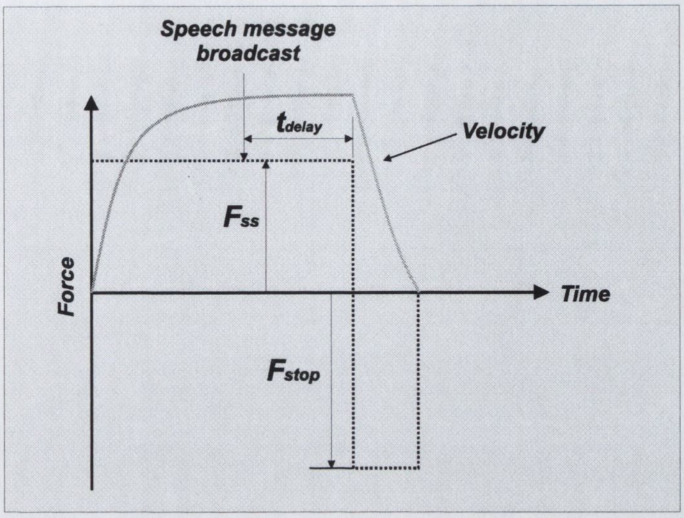


Figure 5.1: Approximation of User Forces in Model to Predict Stopping Distance

coefficients.

The problem being addressed here is slightly different to the closed loop systems associated with manual control. Manual control tasks typically involve an operator tracking the error in the output of a human-machine system [92]. The process which is to be modelled here is of an open loop nature — the system must be able to predict the stopping distance at anytime given the current velocity of the user. Once the voice message to stop has been broadcast, there is no way of compensating for unexpected user behaviour i.e. it is assumed that the user is behaving in an optimal manner.

A typical scenario might be that of the user reversing with the robot into a translation subgoal as described in Section 4.2.3. The robot must command the user to stop such that the robot comes to a halt within that subgoal

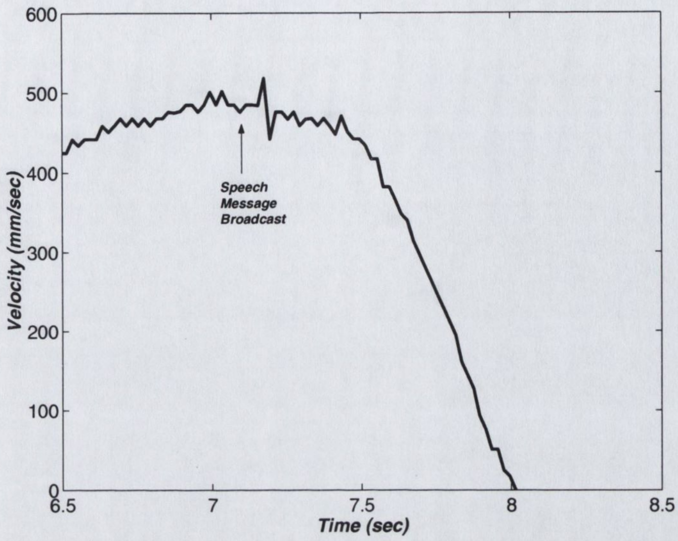


Figure 5.2: Velocity Profile of Robot Upon Commanding User to Stop

region. It is assumed that the user is reversing at a constant velocity, v_{ss}, produced by a steady-state force, F_{ss}. A time delay, τ_{delay} denotes the time taken for the user to react to the *stop* command. To a first approximation, it is assumed that the user changes the direction of the applied force from F_{ss} to F_{stop} instantaneously as shown in Figure 5.1 and the ratio of the stopping force to the steady state propulsive force is a constant, $F_{stop} = const \times F_{ss}$. This is plausible as the user, upon hearing the command to stop will endeavor to bring the robot to a halt within the next step taken (this was observed). The greater the velocity (larger F_{ss}), upon hearing the message, the greater the stopping force (F_{stop}) required to bring the robot to a standstill within the next step taken. An example of real data showing the velocity profile of the robot upon commanding the user to stop is shown in Figure 5.2. The system is modelled as a straight-forward damped mass with first-order velocity behaviour given by

$$m\dot{v} + Dv = F(t) \tag{5.1}$$

where as usual, m is the mass of the system, D is the damping coefficient and v is the velocity. $F(t)$ takes the form of a step function as shown in Figure 5.1. This equation can readily be solved by using the Laplace transformation [50, 78] of the velocity while taking the initial conditions of the problem into account.

$$sY(s) - v_{ss} + \frac{D}{m}Y(s) = -\frac{F_{stop}}{ms} \tag{5.2}$$

where v_{ss} is the steady-state velocity produced by the applied force, F_{ss}. Solving for Y(s) gives

$$Y(s) = \frac{v_{ss}}{(s + \frac{D}{m})} - \frac{F_{stop}}{m}\left(\frac{1}{s(s + \frac{D}{m})}\right) \tag{5.3}$$

Thus, Y(s) is composed of a component with first order behaviour in addition to a component with second order behaviour. Using the reverse Laplace transform, the first part will yield the solution

$$v_I(t) = v_{ss}exp^{-\frac{D}{m}t} \text{ where } v_{ss} = \frac{F_{ss}}{D} \tag{5.4}$$

The second part of Equation 5.3 yields

$$v_{II}(t) = \frac{F_{stop}}{D}\left(-1 + exp^{-\frac{D}{m}t}\right) \tag{5.5}$$

Adding the two solutions gives the result

$$v(t) = v_I(t) + v_{II}(t) = -\frac{F_{stop}}{D} + \left(\frac{F_{stop} + F_{ss}}{D}\right) exp^{-\frac{D}{m}t} \tag{5.6}$$

Substituting $F_{stop} = C \times F_{ss}$ where C is the constant of proportionality gives

$$v(t) = \frac{-CF_{ss}}{D} + \left(\frac{CF_{ss} + F_{ss}}{D}\right) exp^{-\frac{D}{m}t} \tag{5.7}$$

Solving for t when $v(t) = 0$ we obtain

$$t_0 = \frac{m}{D}\left[ln\left(\frac{C+1}{C}\right)\right] \tag{5.8}$$

This is the time taken for the system to come to a halt. The velocity has reached zero but the acceleration is non-zero. It is assumed therefore, that as the robot velocity approaches zero, F_{stop} goes to zero. This is not explicitly modelled as the exact behaviour of F_{stop} at small velocities will not have an appreciable effect on the final result. Integrating Equation 5.7 gives the total distance travelled from the moment the applied force switches from F_{ss} to F_{stop} gives

$$x_{final} = \int_0^{t_0} v(t)\,dt = \frac{m}{D}\left[1 - C\left(ln\left(\frac{C+1}{C}\right)\right)\right] \times v_{ss} \tag{5.9}$$

If the delay associated with the processing of the voice message is approximately constant, it can be included in the above equation to give

$$x_{final} = \frac{m}{D}\left[1 - C\left(ln\left(\frac{C+1}{C}\right)\right) + \frac{D\tau_{delay}}{m}\right] \times v_{ss} \tag{5.10}$$

which is linear in v_{ss}, the velocity of the system (user and machine) before the voice command was issued. Similarly, for rotation on the spot by the user in response to a voice command, one obtains the equation

$$\theta_{final} = \frac{J}{D_{rot}}\left[1 - C\left(ln\left(\frac{C+1}{C}\right)\right) + \frac{D_{rot}\tau_{delay}}{J}\right] \times \dot{\theta}_{ss} \tag{5.11}$$

where $\dot{\theta}_{ss}$ is the angular speed, J is the moment of inertia of the robot about its centre of rotation, D is the damping coefficient and θ_{final} is the angular displacement from the time the voice message was broadcast. Again, it can be seen that there is a linear relationship between the displacement and the velocity.

The coefficients of the above equations can be quite difficult to measure, particularly, J, τ_{delay} and the damping coefficients. Furthermore, some of the coefficients might not be constant over time. For instance, τ_{delay} may vary with system usage. As users becomes more accustomed to the voice commands, they start to anticipate them i.e. they will not have to wait for the completion of the command before reacting to it. Also, the mass and moment of inertia may vary with time. The user might require more support sometimes, thus the load on the system will vary. The damping coefficients will also change depending of the type of floor surface. For instance, carpet will provide higher resistance than wood. What is proposed to address this problem is a system which adapts over time to user behaviour. The model proposed above describes the linear relationship between displacement and velocity. The coefficients of proportionality are difficult by themselves to measure but when lumped together, they can be measured quite easily. When the device is in use, the system can automatically record data points and calculate a linear least-squares fit.

5.3 Experiments

A single case study was carried out to verify both the linear model and the rotation model. The test subject was female and eighty three years old. She suffered from mild glaucoma in both eyes and was able to walk for short distances without assistance.

5.3.1 Experimental Procedure

Two experiments were carried out, one with the linear model and a second with the rotation model. The linear model was verified as follows — the PAM-AID randomly generated a reversal distance R. The user was then commanded to reverse. Upon reversing the distance R, the PAM-AID would broadcast a voice message commanding the user to stop. The system recorded the robot velocity when the voice message was broadcast and the distance travelled between the broadcast of the message and the robot coming to a halt. This was repeated for a range of reversal distances and a range of velocities. A similar procedure was carried out for the the verification of the rotation model. The direction of rotation and the angular distance to be rotated were randomly generated by the robot. The robot then commanded the user to in what direction to rotate. Upon reaching that required angle, the user was commanded to stop. The angular velocity at the time the stop command was broadcast and the stopping distance were recorded. In all, 50 data points were recorded for the first experiment and 75 for the second.

5.3.2 Results

Translation Model

A plot of linear displacement as a function of velocity on command broadcast is shown in Figure 5.3. A linear least-squares fit was performed on this data. What is noticeable from the plot is the presence of a couple of points which could be classified as *outliers*. It is expected that the user will behave in an optimum manner most of the time where it can be expected that the linear hypothesis holds. There are occasions however when the user's response may be unexpected. A command message might not have been heard or something on the floor may have obstructed the wheels. These discrepancies should not be allowed to bias the user model. Outliers can be detected by examining the *residuals* of the least-squares fit. The residual is defined as the difference between the observed values and those predicted by the linear model.

$$r = x - \hat{x} \tag{5.12}$$

where x is the measured stopping distance and $\hat{x}$ is the stopping distance predicted by the least-squares fit. Using a 95% confidence interval the line fit produced a slope of 0.91 ± 0.12 and a y-intercept of -26.01 ± 30.37. The 2 residuals associated with this confidence interval are highlighted in the plot of residuals in Figure 5.4. These points are removed from the data and the line fit is recalculated giving a slope of 0.91 ± 0.11 and a y-intercept of -24.4 ± 25.8.

An important question to answer is how many points are required before the system is making reasonable predictions about the user's stopping distance as a function of velocity. This really depends on how quickly the velocity range of the user is spanned by experimental data. Naturally, if the user's velocity is more or less constant for the first n readings and on the $n + 1^{th}$ reading the velocity is much higher, an accurate prediction might not be possible but subsequent predictions will be more accurate as a result. Figure 5.6 shows the decrease in prediction error as a function of sampled data. The cumulative error on a set of data points is calculated. The error being the difference between the predicted stopping distance and the actual stopping distance. After a new reading is acquired, the least-squares fit is recalculated. After 40 iterations the standard deviation associated with each point is less than $40mm$. This was calculated by dividing the residual sum of squares by its number of degrees of freedom (number of observations less the number of parameters estimated, $48 - 2 = 46$) [17].

Rotation Model

The results from the rotation experiment were processed in exactly the same way. A plot of angular displacement as a function of angular velocity on command broadcast is shown in Figure 5.3. Again, a 95% confidence interval was used to calculate the slope and y-intercept, producing values of 0.88 ± 0.11 and -2.27 ± 2.70 respectively. No distinction was made between right and left although when dealing with people with certain pathologies such as stroke and arthritis, a distinction should be made. The residual plot associated with a 95% confidence interval is shown in Figure 5.8. The four highlighted points were rejected. The line fit after removal of the residuals is given in Figure 5.9.

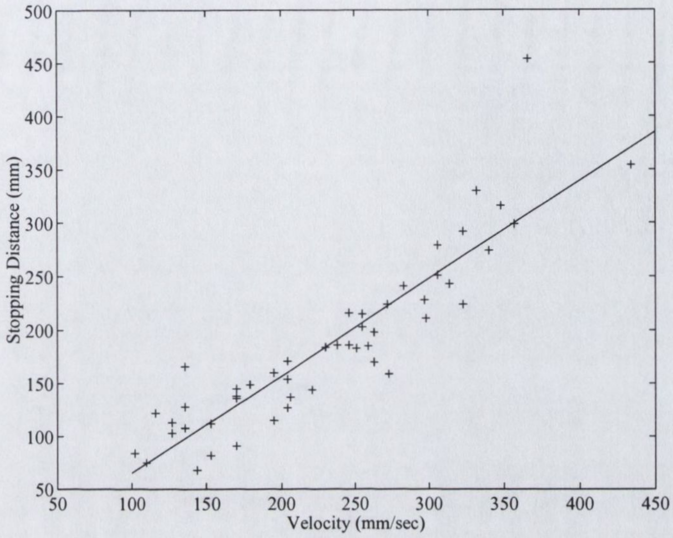


Figure 5.3: Fitting to reversal data

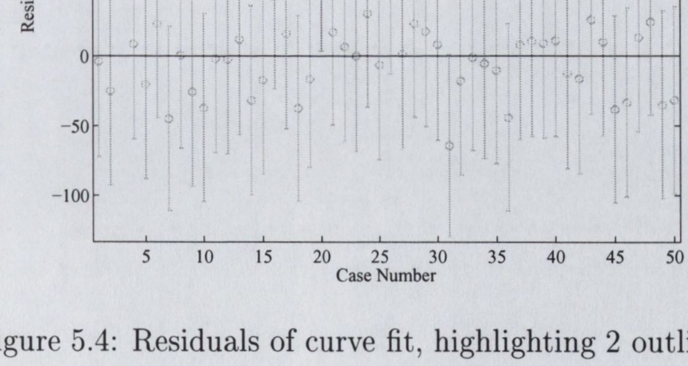


Figure 5.4: Residuals of curve fit, highlighting 2 outliers

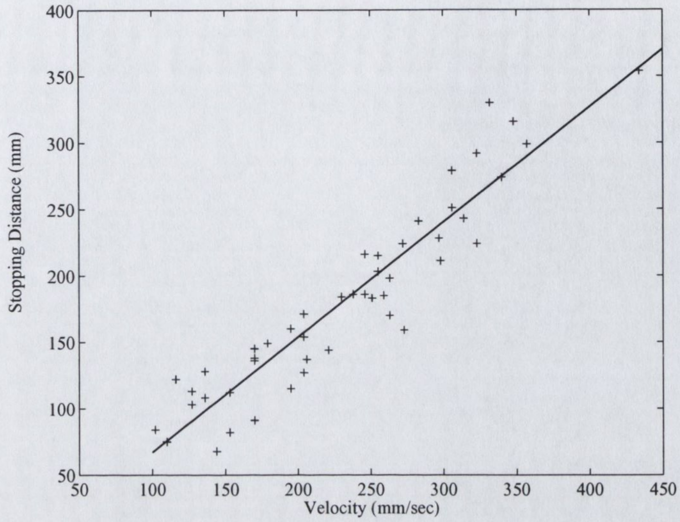


Figure 5.5: Fitting to reversal data with outliers removed

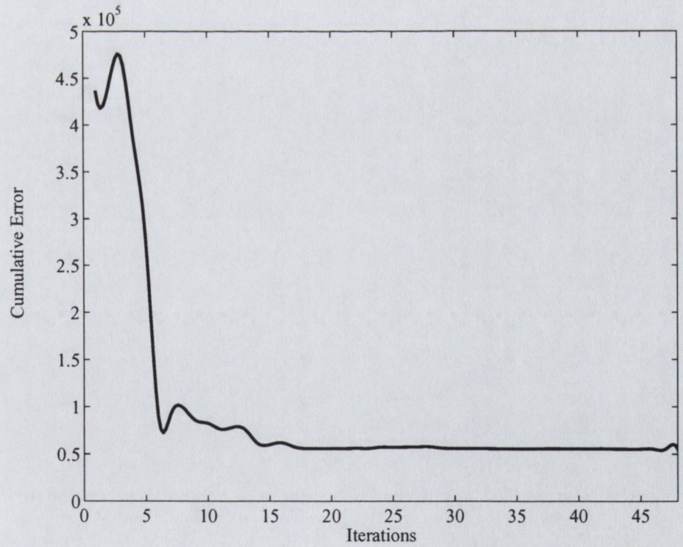


Figure 5.6: Error on test data set with curve fit

This produced a slope of 0.85 ± 0.08 and a y-intercept of -1.59 ± 2.04. The standard deviation was $4.75°$. This figure for the standard deviation correlates well with the minimum width of a rotation preimage ($\sim 10°$) as described in Section 4.2.3. The cumulative error as a function of data samples is shown in Figure 5.10.

Conclusion

The translation and rotation models for predicting stopping distance following the broadcast of a command to halt work extremely effectively. The ability of the models to adapt dynamically to changing user behaviour means that system accuracy is not compromised by changing environmental conditions such as different floor surfaces, different loads being applied to the rollator and even changing user dynamics. The model can be updated in real-time and requires minimal system overhead.

5.4 Manoeuvre Execution

The manoeuvre execution module is called once a successful plan has been generated. Its task is to guide the user through the manoeuvre procedure. The user is cued by voice commands. The robot position and velocity are sampled at approximately 50Hz. For each manoeuvre, a goal reverse translation is calculated (if a reversal is part of the manoeuvre). This goal position is the midpoint of a translation subgoal. On reversal, the system is constantly monitoring the distance between its current position and the goal position. It

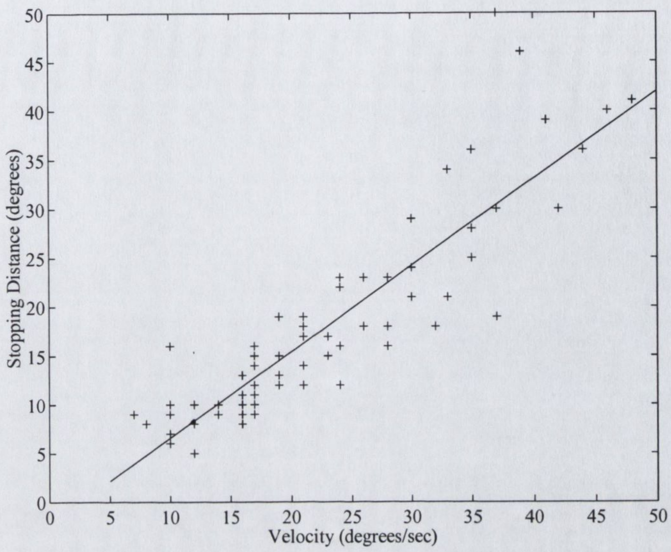


Figure 5.7: Fitting to rotation data

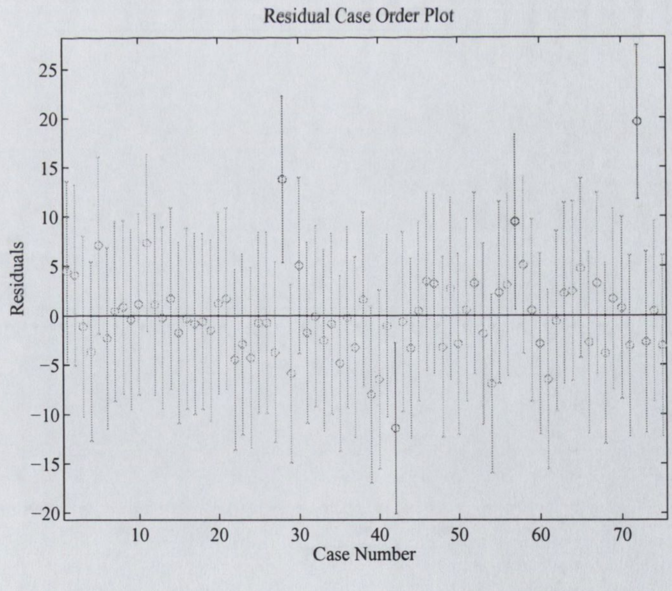


Figure 5.8: Residuals of curve fit highlighting 4 outliers

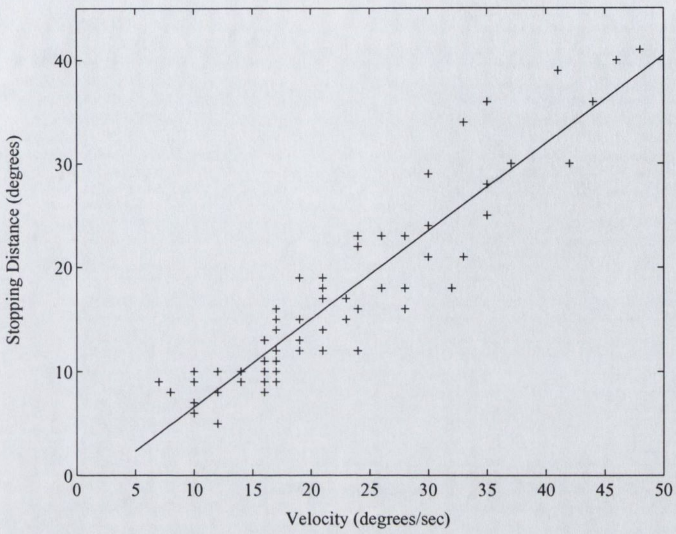


Figure 5.9: Fitting to rotation data with outliers removed

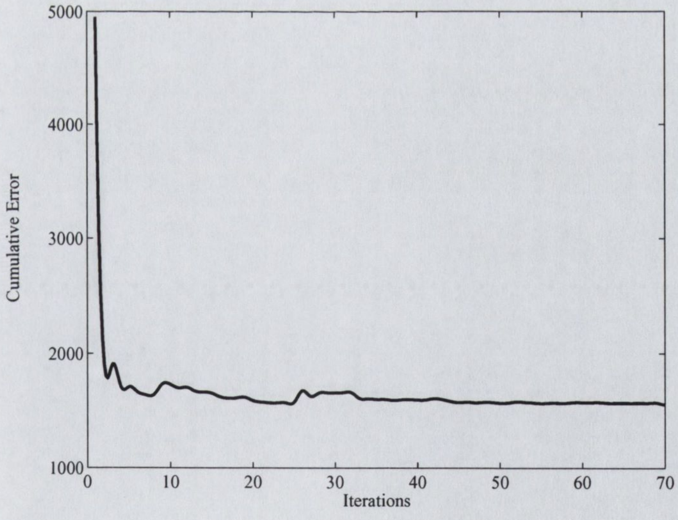


Figure 5.10: Error on test data set with least-squares fit

is also predicting the current stopping distance based on the user model which takes the user's current velocity as input. When the distance to goal is less than or equal to the current estimated stopping distance, the user is prompted to stop.

On completion of the reverse translation phase of the manoeuvre, the user is prompted to rotate-on-the-spot with the robot. The user is also informed in which direction to rotate. Angular position and angular velocity are sampled, again at 50Hz. Analogous to the translation component to the manoeuvre, the user model is used to predict the stopping distance for the system. The user is again commanded to stop.

The final stage of the manoeuvre is the forward component to join up with the goal trajectory. The distance to travel is stored in a lookup table. The system uses the laser to verify that the area to be swept out by this part of the manoeuvre is free. Upon traveling the required distance, the system automatically reverts back to the standard navigation algorithm and proceeds. Feedback is provided to the user, indicating that the manoeuvre was completed successfully.

5.5 Summary

This chapter presented the model used to describe the dynamic behaviour of the human-machine system when the user was requested to stop. The model allowed for the system to learn a user's behaviour over a number iterations. The characteristic positioning accuracy of the system when using the model was $\pm 35mm$ on reversal and $\pm 4.75°$ on rotation. The next chapter examines the performance of the manoeuvre planner and trajectory execution module in field trials.

Chapter 6

User Evaluation and Usability Trials

6.1 Introduction

This chapter describes the usability trials carried out in Ireland and Sweden during the development of the passive PAM-AID concept. When designing for the elderly, it is difficult to foresee many human factors issues which fundamentally influence the usability of a device such as the PAM-AID. Therefore, the involvement of the end-user throughout the design process was essential if user satisfaction were to be achieved. User involvement began even before a prototype was built. A user requirements study was carried out in an effort to gain an understanding of user needs and wishes. This was followed by *interactive evaluation* during the actual development phase. The adopted strategy was similar to that suggested by Engelhardt and Edwards [32]. They advocate a methodology composed of iterative design cycles with the end-user playing an integral role in the assessment of every stage in the device development.

Evaluations were carried out at key stages in the development of the passive PAM-AID. The first trial, for instance, focused on the suitability of the mechanical design and the user interface. Subsequent trials focused more on higher-level functionality of the robot such as the navigation system and the manoeuvre planner. As a rule, the actual evaluations were carried out independently by mobility specialists and occupational psychologists specialising in sensory disability. This allowed for a more objective and comprehensive evaluation. The format for the user evaluations consisted firstly of the test subject using the PAM-AID, this was followed by semi-structured interview with a member of the professional evaluation team. The questionnaires used were prepared by human factors specialists from the Sensory Disabilities Research Unit at the University of Hertfordshire (UK) and were based on Nielson's five usability attributes [75] :

- *Learnability*: The system should be easy to learn so the user can rapidly start benefiting from the system
- *Efficiency*: The system should produce a marked increase in the efficiency of task achievement.
- *Memorability*: The system should be easy to remember so that the casual user does not have to go through repeated training before using the device.

- *Errors*: The system should have a low error rate. If errors are made, the system should be able to recover from them. Catastrophic errors must not occur.

- *Satisfaction*: The system should be designed so that it is pleasant to use. This is very subjective but it can be the deciding factor as to whether the system is a success or failure.

The most important function of the field trials was the identification of core usability problems rather than the production of statistically significant test results. In addition to the questionnaire, it was important to observe users and be aware of possible conflicts between the user's mental model of how the device should operate and the designer's model of expected user behaviour.

The number of participants in each trial depended largely on the availability of suitable candidates and the amount of time required for each evaluation but ranged from 4 for the manoeuvre planner trial to 12 for the long duration trial. It has been reported in the literature that approximately 80% of HCI usability problems can be exposed by between 3 and 5 evaluators [10, 100].

6.2 User Requirements Study

Prior to any design and construction of a walker, a thorough user requirement study was carried out in the UK, Ireland and Sweden. Interviews were carried out with potential end users and their care-givers. All the interviewees could be classified as frail and they all used a mobility aid of some kind. The complete results of the study are presented in [80]. The main conclusions of the study are presented below.

The main concern expressed by those interviewed was that of falling and injuring themselves. Falls are a leading cause in accidental death in the elderly population [1]. They mentioned the embarrassment they felt when falling in front of others and the humiliation of depending on care givers in such situations. In general, potential users preferred the idea of being supported by two handles but suggested that the aid be adaptable to those with only one able hand. Care-givers emphasized the need for easy adaptation of the user interface to users needs. They stressed arthritis as a major factor in determining whether the device could be used successfully by an elderly person.

Potential users expressed interest in a speech interface as a method of communication with the PAM-AID. They were more enthusiastic about voice output than voice input and some expressed reservations about using it in public. Potential users who had been visually impaired for a long time found the idea of a speech interface more attractive than those who had been visually impaired for a shorter period of time. The type of information considered beneficial was information that helped the user navigate safely in the environment, providing warnings for stairs, holes in the ground and other obstacles which might cause the user to trip and fall. Most of those questioned expressed their preference in pushing the device as opposed to being pulled along by the device.

6.3 General Evaluations

6.3.1 Concept Prototype

This section describes the first evaluation of the passive PAM-AID. The purpose of this field trial was to evaluate the concept of a mechanically passive robotic mobility aid for the frail VIP (visually impaired person). The field trials were carried out by professional mobility specialists from the National Council for the Blind of Ireland in Clonturk House, Drumcondra, Ireland. It was important to evaluate the system at this stage and demonstrate that it could be of benefit to people before development proceeded any further. The robot did not at this point have a fully functional navigation system. The autonomous mode of the robot was simulated in a *Wizard of Oz* manner - the steering of the robot was controlled by a technician with a handheld controller. The system tested is shown in Figure 6.1.

There were seven participants in this trial. They were all male with an average age of 82 years. All seven were registered as visually impaired, four were totally blind and the remaining three had limited residual vision. They were all living in a residential home which catered especially for the visually impaired. They had a variety of additional physical conditions - arthritis, frailty, balance problems, nervousness and general ill-health. One participant had recently suffered a fractured hip.

The users had the opportunity to try the device in both manual and Wizard of Oz mode. They also evaluated the effectiveness of the park mode.

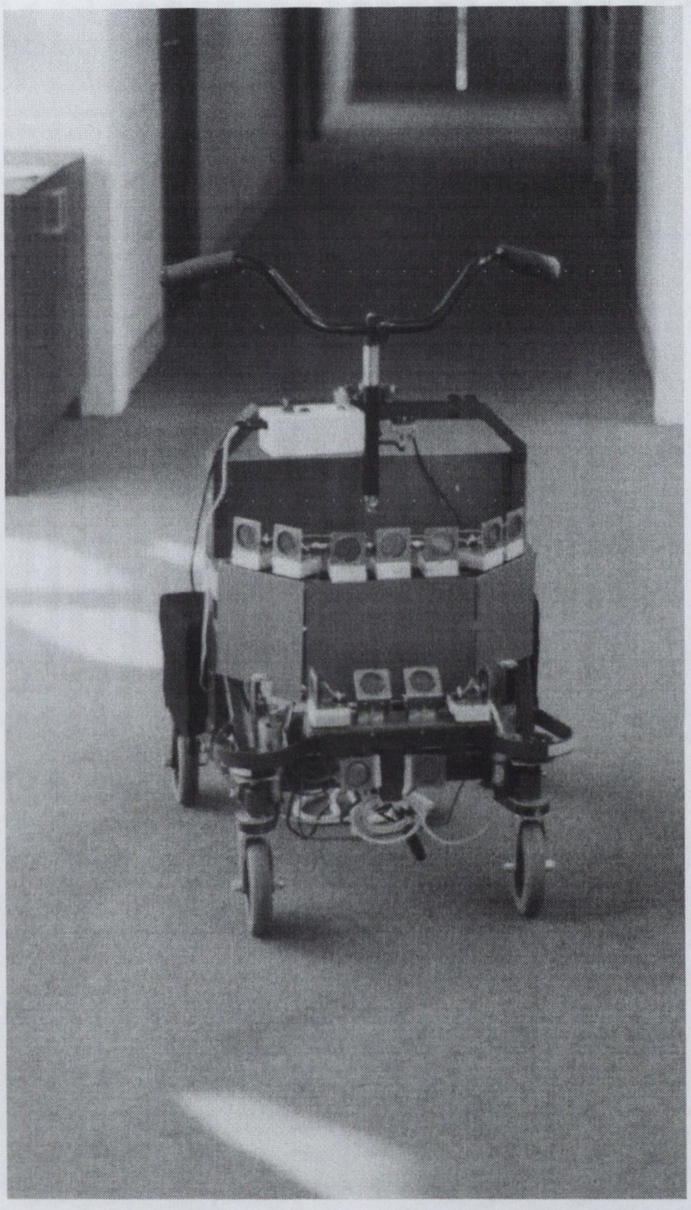


Figure 6.1: Concept Design

In this mode, the wheels were oriented such that no movement of the device was possible. This function was employed for use in situations where the user had to transfer from a chair or bed to the PAM-AID and required that the device provided steady support during this process. The users evaluated different aspects of the device using a 5 point Likert scale. See Table 6.1. In general, an attribute value of 3.5 or above was deemed acceptable, otherwise, that attribute would be prioritized as in need of further improvement. An example of one of the questionnaires is given in Appendix A. A summary of the most important findings of this field trial are presented in Table 6.2.

1	2	3	4	5
Very Low	Fairly Low	Moderate	Fairly High	Very High

Table 6.1: Five Point Likert Scale

Usability Attribute	**Mean Rating**
Ease of operation in manual mode	3.5
Ease of Learning	3.8
Ease of remembering	4.2
Safety	4.4
Perceived usefulness	3.8

Table 6.2: First Evaluation of Passive PAM-AID

Users who were totally blind preferred to use the device in automatic mode whereas users who had some residual sight preferred the manual mode in which they had more control. Six out of the seven participants in the trial liked the concept of using the handlebar to steer the device. They felt it was a very intuitive and natural way of controlling the PAM-AID. They believed that device would be more appropriate in a larger building such as a residential home for the elderly or in a hospital.

This trial was carried out before there was any voice message feedback to the user. As a result, users would constantly put their hand out and feel the wall in an attempt to localize their position in the residential facility. Some of the VIPs were attempting this while moving forwards. This could be potentially dangerous as the VIP is not being supported adequately by the rollator. This behaviour was subsequently eliminated with the introduction of voice feedback which would inform the user of any junctions or the close proximity of any obstacles.

From this trial it was clear that the device had a number of shortcomings. One major problem was the manoeuvering of the device close to a chair etc. This was a problem both for the users of the device and also for the care-givers who would frequently have to manoeuvre the device from the front. This problem was addressed with the introduction of the *turn-on-the-spot* function (section 3.4). This greatly improved the device's manoeuvrability both from the point of view of the user and the care-giver.

It was apparent from observing users with their normal mobility aids and with the PAM-AID that the PAM-AID could make an enormous difference in the efficiency of ambulation. Participants who would normally use the corridor rail for addition support walked with a much improved gait and posture when using the PAM-AID in Wizard of Oz mode. The challenge then was to develop a system which had the sensing and navigational capacity to emulate the capabilities of the Wizard of Oz controller.

6.3.2 Swedish Trial of Rule-Based System

The Swedish trials were conducted by human factors specialists from the Department of Human-Centred Technology, Chalmers University, Gothenburg. The trials were conducted on the university campus. Five VIPs participated in these trials - four female and one male. Three of the women used a rollator as their main walking aid. One woman used a wheelchair and the male VIP used two crutches for support. All participants had used a rollator in the past. Only one of the participants had no residual vision whereas the others were partially sighted and were able to detect walls and larger objects in close proximity. Three of the participants lived in their own homes while two lived in a assisted living facility.

The trial evaluated the sonar based system that used the rule-based algorithm for navigation. The technical details of this system have already been described in Section 3.8.1. This trial again indicated that the two modes of operation (manual and automatic) targeted two different user groups. Most of the participants found the manual mode[1] easier to use. These users however were not completely blind. They found that the added cues given by the speech messages provided sufficient support for the user to navigate safely in a typical

[1]While the user had complete control over the device in manual mode, voice feedback was still being provided. This provided information on their proximity to objects and the presence of features in the local environment

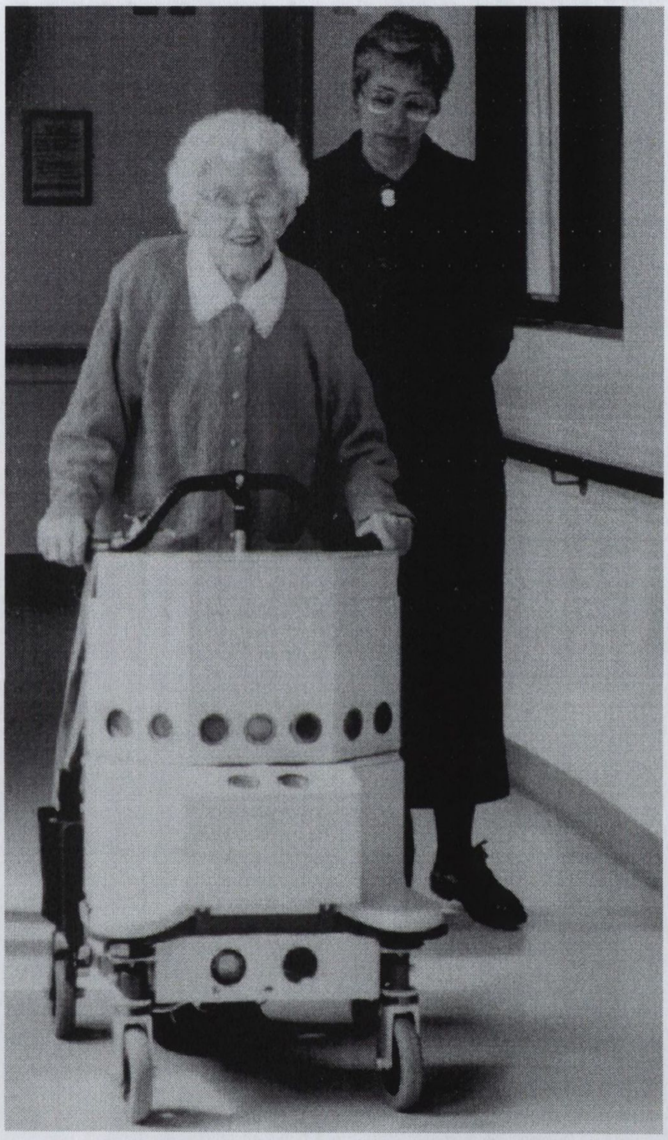


Figure 6.2: Sonar based system

indoor environment. The individual who was completely blind could not use the manual mode effectively and would require the device to be exclusively in automatic mode for it to be of benefit to him. The manual mode would be purely for care-givers to manoeuvre the device for the user.

The participants were unanimous about the weight of the PAM-AID. The frame of the rollator was made of steel and the faring was constructed of sheet aluminium. The total weight of the rollator was approximately 40kg. The weight of the PAM-AID was the main reason behind the participants hesitation when asked if the device would be of potential use to a frail VIP.

One major complaint of the participants in this trial was that the speech messages alerting the user of a particular corridor feature (e.g a left junction) would be triggered only after the user had passed the feature in question. This was due to the sonar arrangement and ultimately the limitation of sonar for differentiating reliably between features. If this was an autonomous service robot, the robot could scan the area more precisely and accumulate evidence for a particular feature. This is not possible with the PAM-AID as the user has control over the velocity and goal direction. In returning the voice message a compromise has to reached between speed of returning a message and the accuracy of the message. It was felt that returning a more accurate message a little late was better than returning an inaccurate message slightly sooner. The users also suggested that the device would be more useful for them outdoors. Sweden advocates community integration for its elderly people even if they have a visual impairment. Consequently, assisted living facilities are quite rare.

The frailty and limited stamina of the test subjects meant that they had very little time to learn how to use the device. It was felt, at this stage in the development, that a more comprehensive trial was warranted where the trial participants could have repeated exposure to the device over a period of a week. This trial is described in the next section.

6.3.3 Long Duration Field Trial

A week long evaluation of the passive PAM-AID was carried out in St. Mary's Residential Home in Dublin, Ireland. The evaluation followed a training program developed by other members of the PAM-AID Consortium[2] and was conducted by human factors and mobility specialists from the Sensory Disabilities Research Unit, University of Hertfordshire (UK) and the National Council for the Blind of Ireland. It was decided to do a week long evaluation of the entire system so that the participants could get more acquainted with the PAM-AID and have more time to explore the device's capabilities. There were 12 participants in this trial, all female with an average age of 79. All twelve participants were registered visually impaired. Four of them were completely blind, the remaining eight had some residual vision. In terms of mobility, two of the participants used a walking stick for support, three used a walking frame, two used a symbol cane[3] and one used a long cane for guid-

[2]Specifically, the National Council for the Blind of Ireland, the Sensory Disabilities Research Unit at the University of Hertfordshire (United Kingdom), the Department of Human-Centred Technology at Chalmers University of Technology (Sweden)

[3]A white cane which identifies the user as visually impaired.

Figure 6.3: Field Trial Of Final Demonstrator

ance. One participant used a wheelchair for traveling longer distances. Four of the participants did not use a mobility aid. Each participant would use the walker for approximately 20 minutes each day. The questionnaire for this trial can be found in Appendix B. The results of this trial are summarized in Table 6.3. The system evaluated was very similar to the one evaluated in Sweden with some modifications to the navigation system which resulted in smoother trajectories being followed.

What was very apparent from this trial was the importance of the voice messages. The repertoire of messages that were used by the PAM-AID were of a general nature. The PAM-AID would alert users to the presence of corridor junctions and obstacles but would require that the user would have a reasonably good idea as to their location . Both participants in the trial and their professional care-givers requested that the PAM-AID give more information specific to their environment. They suggested that the voice messages be of the form "canteen", "lounge", "toilet" etc. Also, the timing of the messages is of great importance. Messages received too late put users in danger as they have to reverse. Backward motion is not recommended by mobility specialists as users are more prone to falling.

Based on the results of both this trial and the Swedish trial, the PAM-AID was completely overhauled. The rule-based navigation system was replaced with the potential field approach using both the laser range finder and sonar sensors for redundancy (section 3.8.3). This resulted in much smoother trajectory following and more accurate feature extraction. The new feature

Usability Attribute	Mean
Ease of pushing PAM-AID	3.1
Manouevrability in manual mode	3.8
Operation of PAM-AID by switches	3.7
Ease of turning on the spot	4.0
Usefulness of spoken messages	4.4
Overall feeling of safety	4.4
Ease of use	3.5
Usefulness	3.8
Personal interest in using PAM-AID	2.9

Table 6.3: Results From PAM-AID Long Term Trial

extraction module alerted the user approximately two seconds before a decision on goal direction had to be made. Much of the aluminium faring was removed and the physical interface was changed to allow users locate switches more easily. The final demonstrator is shown in Figure 6.3.

6.4 Manoeuvre Planner Usability Trial

The planner and cooperative trajectory tracker were evaluated on site by four potential users. The trials took place at St. Mary's Home for the Blind in Dublin. The participants had varying degrees of visual and physical impairment. All participants were female. Participant A was 84 years old. She reported having no residual vision and needed assistance navigating. She did not however require any sort of mobility assistance. Participant B was 66 years old. She also had no residual vision and required no assistance walking. Participant C was 87 years old. She had some residual vision which depended strongly on lighting conditions. She normally used a walking stick and suffered from arthritis in one arm. Participant D was 78 years old. She had low vision (she could no longer read but could make out obstacles in her environment). She suffered from arthritis in her legs and back and required a walking stick for support. Both Participants A and C had used the PAM-AID on a previous to this field trial.

6.4.1 Experimental Setup

The experiment took place in a common room which was a part of the residential facility. Minimal changes were made to the furniture layout so that the test scenarios were as realistic as possible. The intention being to test the device in the level of obstacle density that is normally associated with a typical residential facility. The experiment was designed in conjunction with Anne-Marie O'Neill of the Sensory Disabilites Research Unit at the University of Hertfordshire (UK). Three local minima were chosen in the room and are shown in Figure 6.4 [4]. These local minima were chosen as they simulated a typical scenario whereby the user might park the robot beside a chair and sit down. On rising, the user must somehow manoeuvre the PAM-AID into open space again. For each user there was an initial training period in which it was explained how to request assistance from the planner and how to respond to commands from the device. This training phase lasted between 10 and 20 minutes depending on the user.

[4]The orientations of the figures are different as robot heading is not externally calibrated and simply depends on its heading when switched on.

Each participant was required to manoeuvre out of the three local minima shown on Figure 6.4 and into the centre of the room. This was done twice, once with the planner and once without. When no planner was used, the user had to rely entirely on feedback from the general obstacle avoidance routine.

6.4.2 Results

The system recorded the time taken to complete the manoeuvre and the number of collisions was recorded by the observers. A summary of the results of these experiments is provided in Table 6.4. What is very apparent from these results is the benefit the device has for the profoundly blind over those users who were partially sighted. The two participants who were completely blind showed a much higher incidence of collisions when trying to escape from the local minima than those participants with residual vision. Also apparent from the table is the increase in efficiency of escaping from the local minima for the two completely blind participants. Following the completion of the experiment, each user was asked a number of questions about the planner and the device in general. These questions are presented in Appendix C. A summary of the findings is shown in Table 6.5. The actual trajectories followed by Participant A for all six parts of the trial are shown in Figures 6.5, 6.6 and 6.7.

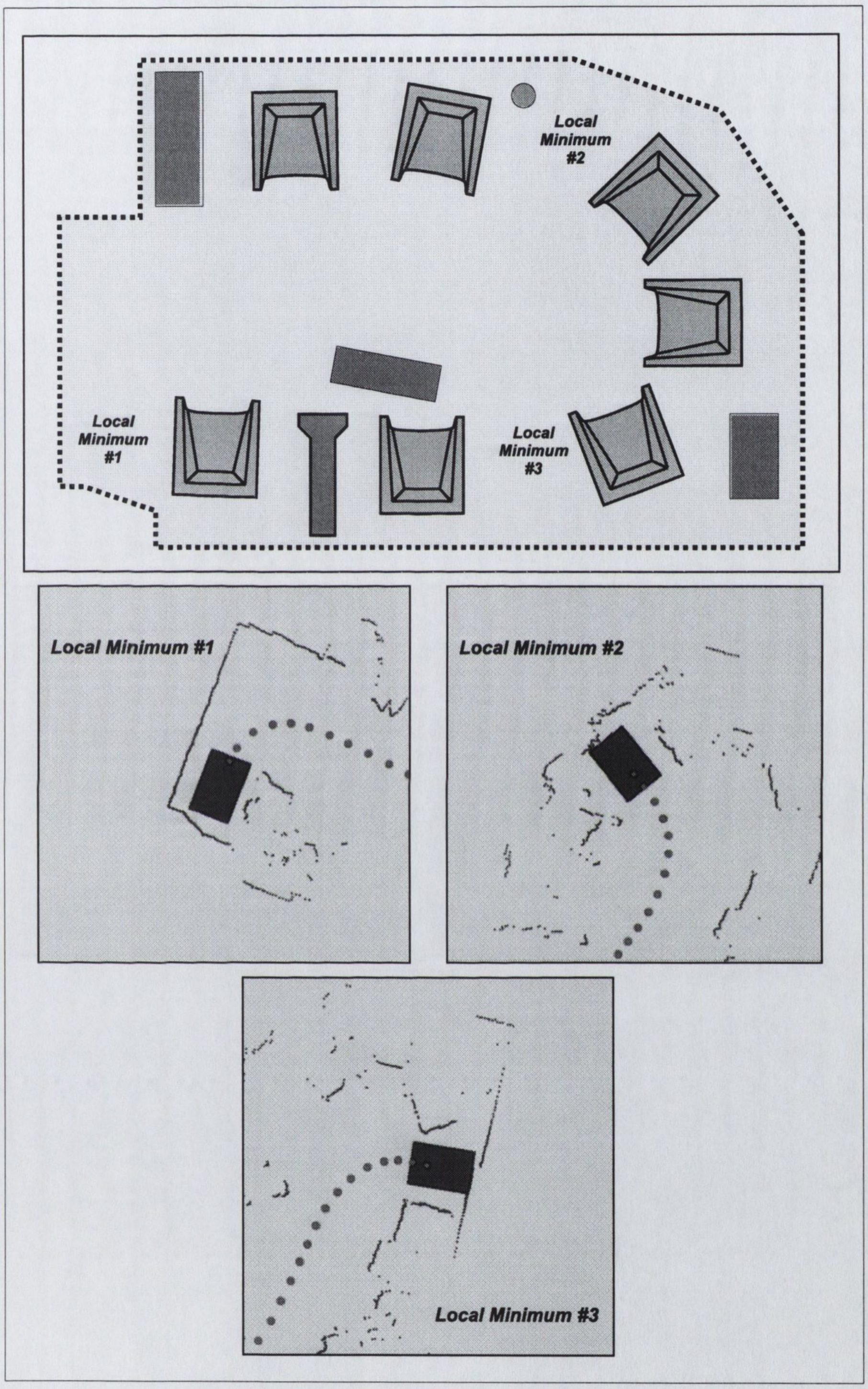


Figure 6.4: Plan of room. The three captured screen shots show the local minima as 'seen' by the robot

Local Min # 1	**No Planner Time (sec)**	**Planner Time (sec)**	**No Planner # Collisions**	**Planner # Collisions**
Participant A	163	44	5	0
Participant B	48	18	2	0
Participant C	24	21	1	0
Participant D	15	21	0	0
Local Min # 2				
Participant A	120	47	4	0
Participant B	32	24	2	0
Participant C	26	17	1	0
Participant D	17	25	0	0
Local Min # 3				
Participant A	150	35	4	0
Participant B	42	27	4	0
Participant C	27	21	0	0
Participant D	58	33	1	0

Table 6.4: Manoeuvre Planner Experimental Results

Voice Feedback

Voice feedback was an integral part of the cooperative trajectory execution. Following the completion of the planner, the robot had to convey to the user what action should be carried out for the task to be completed. The voice feedback was limited to 6 messages - *Reverse*, *Rotate Left*, *Rotate Right*, *Forwards*, *Stop*, *Help Requested* and *Finished Help*.

During the training phase, one user was getting confused between the *Reverse* and *Rotate* commands, possibly as they are quite similar sounding. It might be better to replace the *Reverse* command with *Backwards*. In general, however, after the initial training phase, all users had understood the mapping

Usability Attribute	Mean	Std Dev
Ease of Use	4.3	0.5
Usefulness	4.3	0.9
Safety	5	0
Reliability	4.6	0.6

Table 6.5: Manoeuvre Planner Usability Results

Usability Attribute	Mean	Std Dev
Learnability	4.25	0.5
Ease of use	4.25	0.5
Rememberability	4.25	0.5

Table 6.6: Switch Interface Usability Results

between the voice commands and the respective actions to be carried out by them. When asked, all users thought the number of voice messages was about right.

Switch Interface

For task completion it was necessary to use two switches - the momentary switch for rotating on the spot and the switch for requesting assistance which initiated the planner. Users were asked to comment on this part of the user interface. The results are summarised in Table 6.6.

In general, users appreciated the simplicity of the switch interface and found it straightforward to use. They thought the switch positioning was good. Currently the switch for assistance is mounted below the handlebar. One user suggested mounting it directly at the top of the handlebar stem for easier access. While the positioning of the rotation switch is good, it could be shaped differently to allow easier depression, especially by users with arthritis.

Discussion

The participants in this trial were asked to comment on the device in general. The specific questions asked are in section 5 of the questionnaire in Appendix C. It is again of interest to examine the responses of the profoundly blind participants (A and B) verses those who had limited vision (C and D).

Participant A found the device quite easy to use (4/5). She found the instructions issued by the system easy to understand. She thought the device would be very useful to her (5/5). She commented that the device would give her a huge increase in independence and increased privacy and felt very safe using the device (5/5). She expressed great interest in using the device.

Participant B found the device quite easy to use (4/5) and thought that when finished would be quite useful (4/5). She expressed interest in using the device in the future (5/5) and considered it very safe to use (5/5). She suggested that help facility (the planner) would be most useful to the profoundly blind and suggested that a method for detecting descending stairs would be of great benefit to the user.

Participant C found the device quite easy to use (4/5) but commented on finding it somewhat heavy, especially when rotating. She believed the device would be very useful (5/5) but commented on the issue of acceptance. She believed it would be quite liberating for some people. She stated that she would not currently need it but might consider it if she were tired or under poor lighting conditions.

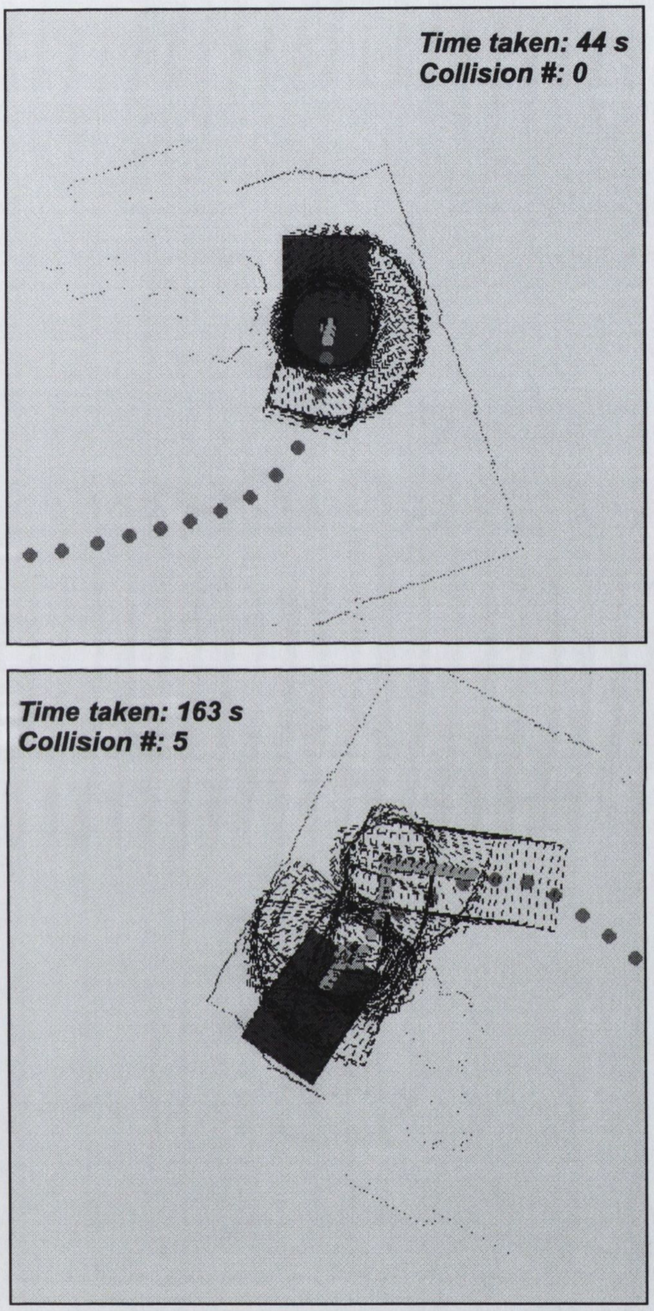


Figure 6.5: Local Minimum #1. Above: With planner Below: Without planner

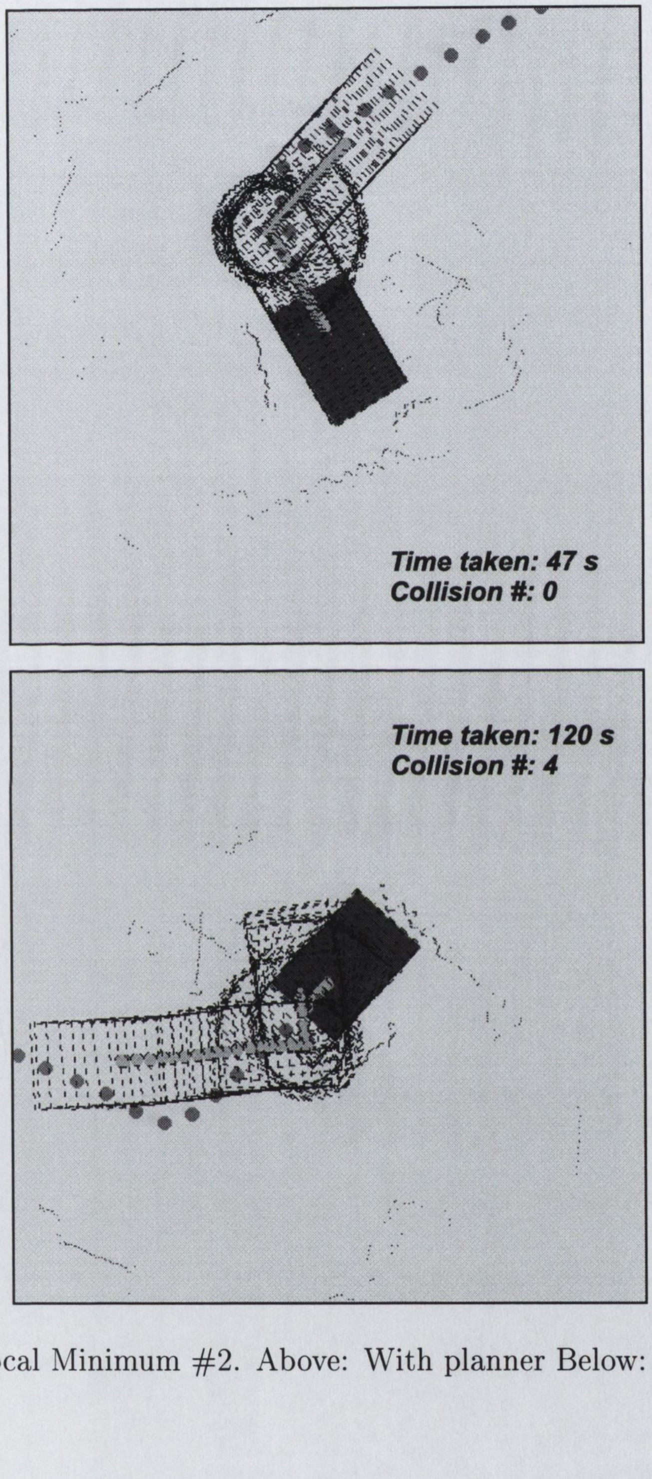


Figure 6.6: Local Minimum #2. Above: With planner Below: Without planner

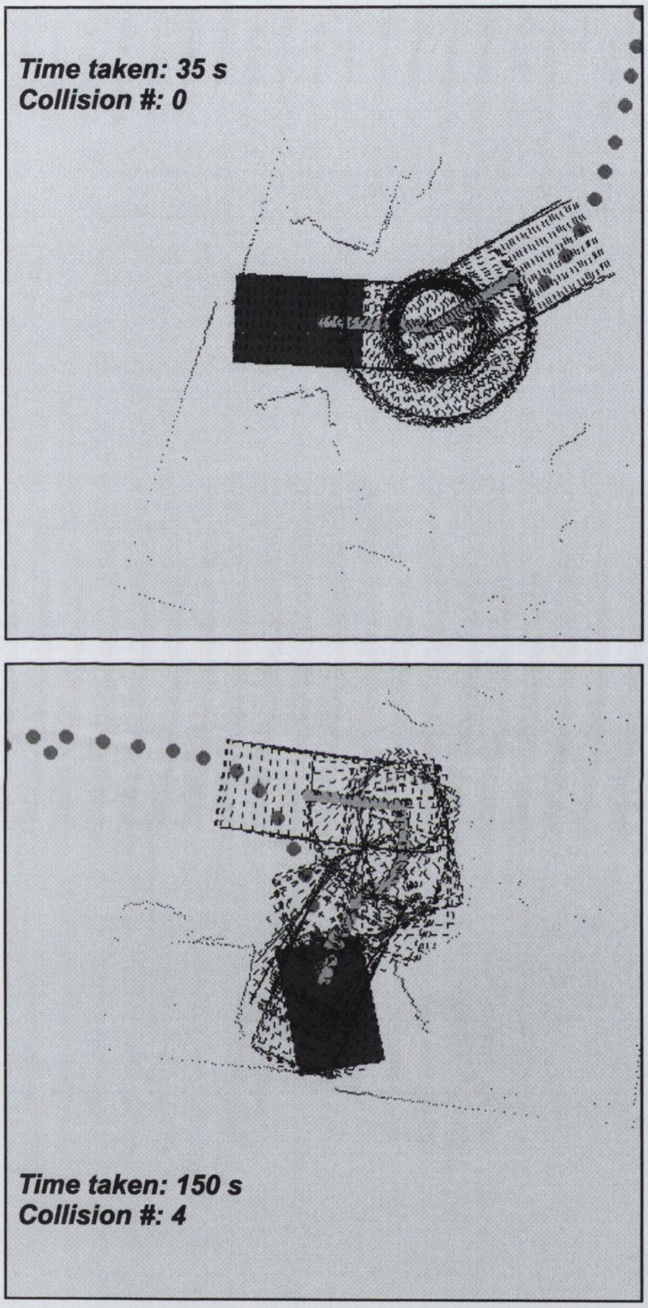


Figure 6.7: Local Minimum #3. Above: With planner Below: Without planner

Participant D found the device manageable to use (3/5). She commented on the overall weight of the device. She thought it would be useful in the future (4/5). She believed the device would be of little use to her in her present surroundings as she knew where everything was and coped well with her limited vision. She thought the device would be useful in unfamiliar environments.

What is quite apparent in discussions with potential users is the whole concept of perceived usefulness. Participants A and B were more enthusiastic about the device as it had the potential to provide them with much safer and efficient mobility. They were both profoundly blind and appreciated assistance from a device which would give them navigational assistance and protect them from collisions with obstacles in the environment. Participants C and D were not as enthusiastic about the device as they had enough residual visual vision so as to be able to navigate familiar environments without much trouble. They did however say that they would be interested in the device should their conditions worsen.

6.5 Conclusions

The usability trials were an invaluable part of the PAM-AID design process. Indeed, the motivation to develop the passive PAM-AID concept came from observing test subjects using the active PAM-AID prototype. It was through field trials that the navigation and sensor systems evolved to allow very smooth motion even in environments with high obstacle density. This helped considerably in understanding what a typical user's physical and cognitive capabilities were.

The development of the user interface benefited greatly from the iterative evaluation strategy. It was important to establish whether or not users had a clear mental model of the mapping between the user interface and device functionality. It was important also to validate the physical aspects of the system. Aside from the standard design principles which had to be applied when developing a user interface for the visually impaired (spatial layout, tactile discrimination etc.), the effects of debilitating conditions such as arthritis which are common in the elderly population had to be considered. It was apparent that a modular design for ease of adaptability was very desirable so as to cater for as wide a user group as possible.

The manoeuvre planner was found to be especially useful to those trial participants with no residual vision. It drastically reduced the number of collisions and the efficiency with which they navigated in environments with relatively high obstacle density and many dead-ends.

Chapter 7

Gait Characteristics

7.1 Introduction

Although the PAM-AID system was developed primarily as a navigation aid for the frail blind, it also has the potential to monitor certain physical characteristics of the user such as gait. Gait can be used as an indicator of a person's well-being. A system which monitors these characteristics on a long term basis might be useful for clinical evaluation of a person's condition over time. The primary function of the work presented in this chapter is to illustrate that certain important gait parameters can be measured using a rollator. It is by no means a comprehensive study. No long term studies were carried out to establish their value in a clinical environment. This was considered beyond the scope of this thesis.

7.2 Gait Pathology

Gait, balance and posture rely heavily on the senses. Vision, vestibular function, limb proprioception and tactile sensing are all important. There is a certain amount of sensor redundancy, allowing for accommodation should one sensing modality cease to function correctly. In the elderly however, disease and the general effects of aging can impair the functioning of a number of these sensory modalities which can have severe implications for a person's balance and gait. The increased susceptibility of people with a visual deficit to falls resulting in hip fractures is well known. Figures supporting this were presented already in Table 2.1.

Good neurological and motor function are also fundamental for gait and balance [106, 19]. Sensor information is processed and integrated at many different levels within the human's neurological system to ultimately produce motor outputs. This whole integration process is distributed between the basal ganglia, the brain stem, the cerebellum and the spinal chord gait generator. Problems within this distributed processing system can lead to serious gait and balance problems e.g. Parkinsons disease which produces a very characteristic shuffling gait. Dynamic balance requires good muscle strength. Advanced muscular atrophy can affect both the strength and the reaction speed of muscles.

Much research has already been done in the area of gait disorders in the elderly. Wolfson et al. [105] have shown that stride length, walking velocity and gait quality were significantly reduced in nursing home residents with a history of falls. Monitoring velocity has been suggested as a very effective method for measuring disease activity and the success of rehabilitation [98]. It may be particularly suitable for monitoring people with cardiopulmonary disease [39]. It has been suggested also, that there is a correlation between the gait dynamics of the elderly and susceptibility to accidental falls [41].

The normal methodologies used for measuring gait parameters require the use of specialist gait labs. A gait monitoring system which was integrated into a mobility aid might provide valuable information on a user's well-being or rehabilitation progress without the necessity for dedicated equipment. One other potential application might be in the area of fall prevention. The gait and balance characteristics of a user might change dramatically prior to a fall. If this could be detected, evasive action could be taken to protect the user from injury.

7.3 Approach

The experiments which follow attempt to ascertain whether any gait-related parameters can be measured with a rollator. The approach taken was to examine whether sensors which might already be present on a device such as the PAM-AID would have the capability for resolving some aspects of gait dynamics. The sensors in question were incremental encoders which are standard on most robots for the provision of odometric data and a force-torque sensor. No force sensing was present on the final passive PAM-AID prototype. Force sensing was however considered for measuring user input on both the active and passive prototypes.

Gait patterns are intrinsically cyclical in nature which is ideal for both time-series and frequency domain analysis. A full gait cycle corresponds to time between consecutive heel strikes of the same foot. In terms of the vertical force being applied to the mobility aid, two load maxima would be expected during this gait cycle. These maxima correspond to the person's weight being transferred onto the left foot and then back onto the right foot. Normal gait would result in a symmetric loading of the mobility aid during the left and right phases of the gait cycle. If the data is of sufficient quality it should also be possible to calculate stride frequency by measuring the time interval between alternate load maxima as shown in Figure 7.3. This data can be time averaged to produce an estimate for the stride frequency variance. A similar approach can be taken when analysing the velocity time series. This should also produce a measurable ripple on the steady state velocity which is again correlated to the phase of the gait cycle. Again, the time between alternate velocity maxima should correspond the stride frequency. Stride length can be calculated very simply by combining the stride frequency data with displacement data.

Asymmetry in the gait of the elderly can have many causes. Limb pain above a certain threshold will generally result in a person attempting to relieve the pain by altering their gait. The more acute the pain, the more asymmetric the gait. Another cause of gait asymmetry in the elderly is inadequate motor function, possibly as a result of stroke. Frequency analysis of the time-series data from both force-torque sensor and the incremental encoders should be capable of exposing such asymmetry.

7.4 Testbed Design

A testbed was constructed to determine whether it was possible to measure gait parameters[1]. The testbed was based on a standard four wheel rollator design with two fixed rear castors and two front swivel castors which allowed the device to be steered. The testbed is shown in Fig 7.1. The chassis was constructed from extruded aluminium profiles which could be bolted together. A six axis force-torque sensor was mounted at the stem of the handlebar and optical incremental encoders were mounted on the rear castor wheels. The rollator was thus capable of measuring the instantaneous velocity of the user as a function of time. This information could be further processed to produce acceleration data. In addition, forces and torques applied by the user through the handlebar as a function of time could be measured. The sensing capability of the testbed thus differed to that of the PAM-AID. While both systems had very similar odometry systems, the PAM-AID employed a Hall-effect sensor rather than a force-torque sensor in the user interface.

7.5 Data Acquisition and Processing

The force-torque sensor (JR3 65E20A, 6-axis, 440N load limit, 880N along the z-axis) returned absolute force and and torque measurements. The condi-

[1]These experiments were carried out while the author was a visiting researcher at MIT. During this time the PAM-AID was unavailable.

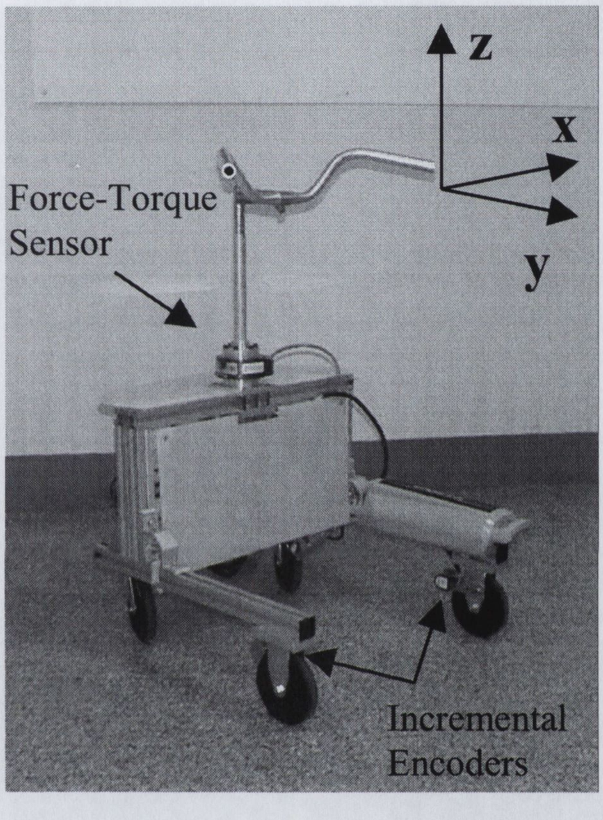


Figure 7.1: Experimental Testbed

tioning electronics (fourth order Butterworth low pass filters [81]) produced 6 independent analog outputs in parallel which corresponded to the 6-DOF being measured $(F_x, F_y, F_z, M_x, M_y, M_z)$. A 32-bit A/D converter board (Diamond Systems MM-32) produced the digital output. The incremental encoders (US-Digital Inc., quadrature, 500 counts per rev.) measured the distance travelled since the last sample time. This information was divided by the sampling period to produce an instantaneous velocity. The absolute distance travelled as a function of time was also stored as it was required for estimating the user's stride length. Both the incremental encoders and the force-torque sensor were sampled at a frequency of 100Hz.

The time-series produced by the force-torque sensor and the incremental encoders (velocity data) were filtered with a second order *Butterworth* filter with a cut-off frequency of 1.5Hz (Matlab[2] discrete Butterworth filter, *butter*). The velocity data was further processed to produce an acceleration time-series. Acceleration data was used in preference to velocity data as it does not contain any dc-bias. The acceleration time-series were calculated by differentiating the velocity data (Matlab differencing function, *diff*). Similarly, the force data was differentiated to remove any dc-bias.

The stride frequency and its variance were determined by calculating the time between every second negative to positive zero-crossing on the acceleration time-series and the differentiated force time-series. See Figure 7.2. Stride length and the corresponding variance were determined from the original odometry data by calculating the distance travelled between every second

[2]URL: http://www.mathworks.com

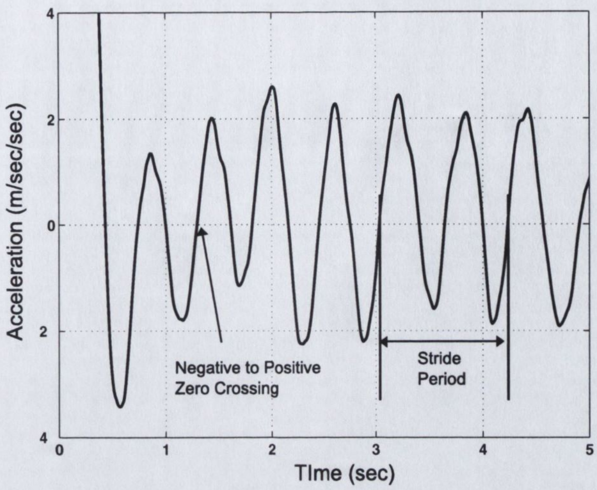


Figure 7.2: Typical Acceleration Time-Series

negative to positive zero-crossing of the acceleration or differentiated force time-series.

An alternative to processing the time-series data directly, is to move into the frequency domain. A frequency analysis approach is valuable when the raw time-series proves too noisy to produce reliable results. In order to convert the data into the frequency domain, a fast-fourier transform(FFT) was applied to the time-series (Matlab function, *fft*). A power spectrum was obtained by taking the product of the FFT with its complex conjugate. A curve was fitted to the FFT data using a cubic spline interpolation (Matlab function, *interp1*). The stride frequency was calculated from the peaks in the power spectrum. An example of a power spectrum produced by a healthy adult is shown in Figure 7.4. For a normal adult gait, a single peak, at twice the stride frequency was expected. Subjects with asymmetric gaits were expected produce power spectra with an additional peak at the stride frequency.

7.6 Experiments

Initial experiments were carried out on individuals with no history of any gait pathology. This was followed by field trials at a residential home for the elderly. The primary purpose of these trials was to ascertain whether data of sufficiently high quality could be obtained from the force-torque sensor and the incremental encoders[3] such that certain gait parameters could be reliably calculated.

7.6.1 Results for Normal Adult Users

The system was first tested on adults in full health in order to establish the qualitative characteristics of a typical, non-pathological gait. The data from the force-torque sensor and the incremental encoders was collected while the test subjects pushed the testbed in a straight line over a distance of approximately 10 metres.

An example of typical time-series data from an individual with no gait disorders is shown in Figure 7.3. The time-series on the left shows the walker acceleration.The acceleration time-series yielded a mean stride frequency of 0.8290Hz with a standard deviation of 0.038Hz and a stride length of 1.15m

[3]In the following discussion, force data refers to data from the force-torque sensor while velocity or acceleration data refers to data from the incremental encoders. The same distinction applies in the section of frequency analysis where the terms force spectra and acceleration spectra are used.

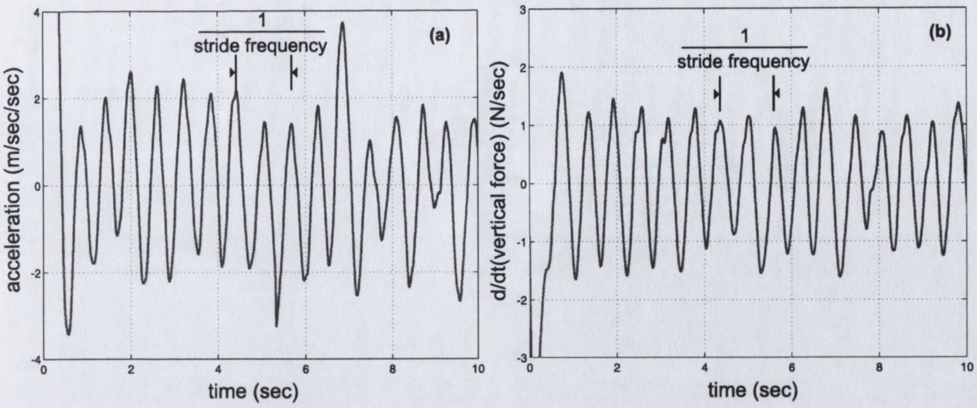


Figure 7.3: (a) Rollator Acceleration (b) Time Derivative Of The Vertical Force Applied To The Rollator

with a standard deviation of 0.12m. The time-series on the right of Figure 7.3 shows the differentiated vertical force applied to the walker by the user. This too can be used to calculate the stride frequency. Using this data a mean stride frequency of 0.826Hz was obtained with a standard deviation of 0.039Hz. The average stride length obtained was 1.097 ± 0.091m for the first time series and 1.1012 ± 0.092m for the second. The data from the two sources correlate well.

A typical power spectrum of the vertical force applied by a subject with a normal adult gait is shown in Figure 7.4. The single peak in the power spectrum occurs at twice the stride frequency. The peak occurs at 1.66Hz resulting in a stride frequency of 0.83Hz. This corresponds exactly with the results obtained from the analysis of the time-series data.

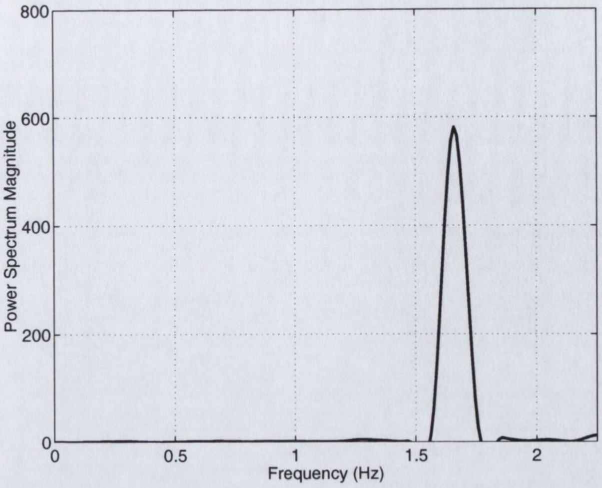


Figure 7.4: Power Spectrum of Vertical Force Time-Series for Normal Adult Gait

7.6.2 Field Trial Experiments

Following successful results on individuals with no history of any gait pathology, the experimental platform underwent testing at Cadbury Common Residential Home in Cambridge, Massachusetts. Seven residents participated in the field trial. Four of the participants required a zimmerframe and two required a walking stick for support. The average age of the participants was 84. Again, the test subjects were requested to push the rollator, in a straight line, at their own pace for approximately 10 metres. This was repeated approximately 4 times for each participant.

Time-Series Results

The time-series produced by the field trial participants contained a lot more structure (more peaks per period). This was especially true for the zimmer-frame users, whose gait quality had deteriorated beyond a certain level. This meant that it was extremely difficult to extract reliable stride frequency data, even when filtered. It would appear that this additional structure is related to the user's particular gait pathology. Processing of the time-series involved calculating the time intervals between negative to positive zero-crossings. This process is easy to automate and works well for data with low noise content. The noise content of the data from these trials made it difficult to process the time-series automatically. An example of such a time-series is shown in Figure 7.5a. Overall, however, the force data was cleaner than the encoder data.

The stride frequency and stride length data can still be estimated from noisy data by using frequency analysis. A discrete fourier transform of either the velocity or the loading force time-series can provide the necessary information to calculate the stride frequency and stride length.

Frequency Analysis Results

The structure of the power spectrum depended on whether any gait asymmetry was present or not. If the gait were perfectly symmetric, all the energy would be concentrated in a peak at twice the stride frequency. However, if the gait were anyway asymmetric, either in terms of the relative phases of the left and

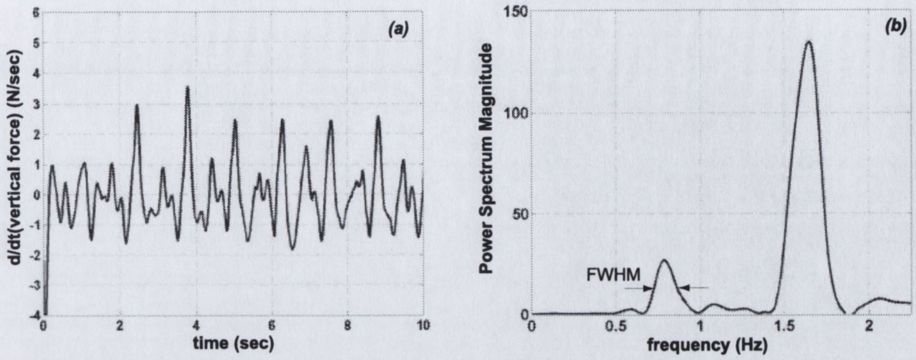


Figure 7.5: (a) Time Derivative Of The Vertical Force Applied To The Rollator. (b) Frequency Spectrum of Time-Series Data

right components of the gait cycle or in terms of the load applied to the device during the left and right components of the cycle, a peak would also be found at the stride frequency along with peaks at higher frequencies (harmonics).

An example of a power spectrum acquired during field trials is shown in Figure 7.5b. This power spectrum shows two peaks, a dominant peak at twice the stride frequency and a second peak at the stride frequency. This is indicative of some sort of gait asymmetry being present (see Figure 7.4 which shows a typical power spectrum corresponding to a normal adult gait). The test subject was female and was recovering from a stroke. She also suffered from frequent petit mal seizures[4]. The time series on the left is the derivative, with respect to time, of the applied vertical force as a function of time. Even after smoothing using a low pass filter, the time-series still exhibited many spurious peaks, not characteristic of the weight transfer patterns of a normal

[4]Short periods of "blanking out"

gait (see figure 7.3b for comparison). As a result, frequency analysis was used to extract stride frequency and then combined with odometry data to obtain the stride length. The mean stride frequency is 0.793Hz. The full width at half maximum(FWHM) is 0.159Hz. This corresponds to a mean stride length of 0.887 ± 0.160 m/sec. Note, the dominant peak occurs at double the stride frequency. The ratio of the two peaks could be used as a metric for the extent of the asymmetry.

A simpler characterisation of asymmetry can also be achieved by time averaging the torque about the longitudinal axis of the rollator (the torque about the y-axis in Figure 7.1). The torque about the y-axis of the force-torque sensor for the same test run as the data shown in Figure 7.5 produced an average dc bias of 5.6Nm indicating that the user was relying more on her left side for support.

7.7 Discussion

Force[5] and acceleration[6] power spectra do not provide the same information. The force power spectrum provides information on the transient vertical loading of the walker while the acceleration power spectrum provides information on the transient propulsive forces being applied by the user (via the equations of motion of the walker). In other words, the force power spectra can be used to monitor the degree of asymmetric loading while the acceleration spectra can

[5]Data from force-torque sensor

[6]Data from incremental optical encoders

be used to see whether power is being transmitted unilaterally or in a more symmetric manner.

While transient loading information is interesting, the prohibitive costs of high quality force sensors means that the information being gathered would need to have a high clinical value in order to justify the use of such a sensor. On the other hand, low cost odometry sensors can provide information on power transmission by the user as a function of time. This information is potentially important in the area of stroke rehabilitation.

What is noticeable about the acceleration power spectra is the large non-stationary component [22] at low frequencies (see Figure 7.6). This non-stationary component results from a change in the user's average velocity. Care must be taken when sampling velocity data to make sure the average velocity remains relatively constant. The force power spectra do not exhibit this phenomenon as the frequency of weight transfer from side to side remains approximately constant over a range of velocities while the step size changes.

7.8 Conclusion

This chapter demonstrated the potential that a smart rollator has for health monitoring in addition to the provision of navigation assistance. Equipped with a force-torque sensor and a standard odometry system, the rollator testbed could measure certain gait parameters of the user such as stride frequency and stride length. Gait asymmetry could also be detected by examining force and acceleration power spectra. Very little research has been published to date on

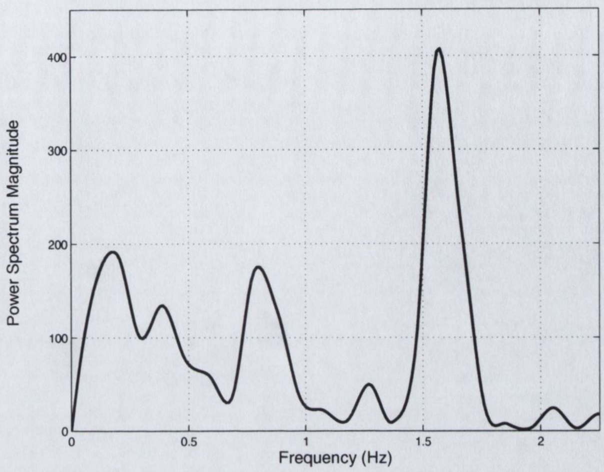


Figure 7.6: Acceleration Power Spectrum

the gait of people using upper body support such as a walker or rollator so the clinical significance of such as device is unclear. The work described here illustrates what can be measured using a device such as the PAM-AID.

Chapter 8

Conclusion

8.1 Introduction

This thesis presented a novel robotic mobility aid designed to address the needs of frail visually impaired people. The passive PAM-AID, as it is called, gives the user both physical and navigational support. The device is the latest in a series of research prototypes exploring how robotics can contribute to increased independence among the elderly. The passive PAM-AID distinguishes itself from previous robots in that it is a mechanically passive device. Its development is summarised below. This is followed by discussion of possible future work.

8.2 Summary

8.2.1 General Design

The motivation to develop a mechanically passive robot came from observations made during field trials of previous *active* PAM-AID prototypes. The two main factors which caused a design rethink were first, the issue of safety, and second, the need for increased human-machine compatibility. The safety issue is best understood in terms of the robot's incomplete world model. Complete sensor coverage is difficult and expensive to achieve. In such a scenario, it is much safer if the user has as much control over the system dynamics as is possible. This was achieved with the passive PAM-AID without sacrificing functionality. The human-machine compatibility issue is essentially the problem of matching user dynamics with machine dynamics. This is especially applicable to the elderly population where physical ability varies greatly. Making the device passive eliminates this problem. A passive system has other advantages such as a reduction in overall weight and lower power requirements. On completion of the chassis and user interface, usability trials were carried out. These trials exposed the need for higher manoeuvrability in environments of high obstacle density. This was achieved with the introduction of the *turn-on-the-spot* facility which reduced the minimum turn radius down to mere 60cm. A Wizard Of Oz experiment was conducted to simulate a working navigation and collision detection system.

A number of navigation algorithms and sensor configurations were evaluated for suitability on the PAM-AID. Usability trials in Sweden and Ireland demonstrated that sonar alone was not sufficient for robust navigation and reliable feature detection. The final demonstrator used a variation on the VFH+ algorithm with a scanning laser range finder as the primary sensor. An array of sonar transducers was used to increase sensor coverage of the user space. This work has been previously published in [68, 69, 70].

8.2.2 The Manoeuvre Planner

While general obstacle avoidance routines do provide the user with assistance most if the time, it could be argued that they fail when the user is in most need of them - where the obstacle density is high enough for the general obstacle avoidance to return with no plan. The manoeuvre planner (Chapter 4) developed for the PAM-AID attempted to address this shortcoming. Although the manoeuvre planner does not currently exploit the robot's full kinematic capability, it is very versatile in its applicability. It does not require a stored global map but instead keeps a history of scans in memory and assembles a map dynamically if the user requires a manoeuvre to be executed. A grid representation was used to divide the workspace into free and occupied space. The occupancy grid was regular and thus provided a conservative estimation of free space. This sufficed for fine-motion planning as long as the grid resolution was appropriate. A trade-off had to be made between grid resolution and computation time. The implemented planner used a cell dimension of 25mm which corresponded to an average total manoeuvre computation time of 4 seconds.

Experiments were carried out whereby users were required to manoeuvre out of a three cluttered scenarios with and without the assistance of the manoeuvre planner. The choice of participants (2 with no residual vision and 2 who with low-vision) highlighted the benefit of the PAM-AID for people with very little residual vision. The participants with low-vision were just about able to make out obstacles and were able to manoeuvre around them. The participants with no residual vision found it extremely difficult to complete the tasks and collided frequently with objects. On the other hand, they had no difficulty navigating when using the manoeuvre planner. Plenty of scope exits for extension of the planner and this is discussed in the further work section.

8.2.3 User Model

A design decision was made not to use brakes on the device except when absolutely necessary[1]. It was felt that constant active intervention from the system would be frustrating for the user. It was found sufficient to make the user aware that local obstacle density was high through the use of voice messages such as *slowly* and *object ahead.* Users intuitively respond to these messages. For the manoeuvre planner to work effectively, a dynamic model of the user (Chapter 5) was required so the system would know when to command the

[1]Potentially dangerous situations where the use of brakes would be deemed necessary include descending ramps and on detection hazardous situations at floor level such as descending stairs etc.

user to cease a particular action. The model, derived from the equations of motion of the robot produced the result that the distance travelled following the broadcast of the voice message was a linear function of the robot velocity when the message was broadcast. Similarly, for the rotate-on-the-spot function, the predicted angular displacement which follows a command to stop is a linear function of the angular velocity at the time the command was broadcast. The constant of proportionality is user dependent. This is very convenient as it means that following a short learning phase, the robot can predict quite accurately when the user will stop. This result was verified experimentally. The prediction accuracy was calculated as $\pm 35mm$ on translation and $\pm 4.75°$ on rotation.

8.2.4 Gait Analysis

Gait and balance are important indicators of a person's well-being. The possibility of extending the functionality of devices such as the PAM-AID to measure certain gait characteristics was explored (Chapter 7). An experimental testbed similar to the PAM-AID was constructed. It used odometry for position and velocity estimation. In addition, a six-axis force-torque sensor was integrated into the user interface. Field trials were carried out to assess whether fundamental gait parameters such as stride frequency could be reliably estimated from acceleration and force time-series. It was found that due to deterioration of gait of typical zimmerframe users, gait parameters could not be reliably measured from time-series alone. A frequency analysis of the time-series data did however allow the estimation of stride frequency and stride length. The frequency analysis also highlighted any gait asymmetry present.

8.3 Future Work

The manoeuvre planner currently takes into account trajectories based on straight-lines and on-the-spot rotations. Currently, a manoeuvre consists of an optional straight reversal, followed by an on-the-spot rotation followed by a straight translation forwards. This could be extended to include trajectories composed of arcs of circles. This would increase the range of scenarios the system could handle. For instance, the straight-line reversal component of the manoeuvre might be replaced by a straight-line followed by an arc of a circle. The straight-line would have to precede any circular arc in order for the user to sense the direction in which the steered wheels were pointed. Also, the radius of curvature of the arc would have to be lower bounded as users find it difficult to simultaneously reverse and rotate when the turn radius below a certain value. Additionally, the final part of the manoeuvre (the straight-line forward translation) could also be replaced by circular arcs in order to improve goal reachability. With the introduction of curved trajectories, it might even be possible to leave out the on-the-spot rotation component of the manoeuvre. A formal mathematical analysis of the problem would be useful to determine what is necessary to guarantee controllability and to determine the optimal set of manoeuvre components given the constraints on the whole system. With the addition of the manoeuvre planner, the system has the capability to *undock* from objects in the user's workspace such as tables, chairs, beds etc. A mode of operation is required by which the user can *dock* with these objects. Docking in this sense means that the robot should achieve a goal configuration such that the user can interact successfully with the object in question. This is a challenging problem as it requires advanced feature detection. Not only must the feature detector recognize the object, it must also determine the pose of the object so that a successful docking manoeuvre can be executed.

Currently the PAM-AID does not have the capability to detect potential hazards at floor level. This would include descending stairs and any discontinuities which might expose the user to injury. This is not a trivial problem as the system developed should function reliably under all lighting conditions and with all surface reflectivities. The sensor arrangement should be such that the system has adequate time to initiate a controlled stop or avoidance manoeuvre.

Users expressed interest in being able to command the robot to take them to a specific location within the building. This requires the PAM-AID to have the ability to know where it is within a building and to have the ability to plan paths between locations. Two approaches can be taken to solve this problem. On the one hand, planning and localization could be carried out locally on the PAM-AID. Ideally, the robot would have a stored map of the building, otherwise map construction and maintenance would also be required. On the other hand, the environment could be made smarter. The PAM-AID could then query the building as to its location and how to proceed to the task goal. In this way, the huge computational load associated with mapping and localization could be avoided. Work on this approach is already in progress and is described in [79].

Coupled with all the increased functionality is the need for a more intelligent user interface. As the device is designed for the visually impaired, the designer cannot use the human's most powerful sensory mode for conveying information. Communication bottlenecks occur very quickly when relying on voice feedback. The problem can be circumvented somewhat on the system side if the feature extraction is sophisticated enough to determine different contexts. In that way certain voice messages are coupled with certain environmental contexts. For instance, a set of voice messages would be associated with corridor navigation, another set would be associated with docking, undocking, etc.

The device was primarily developed for the frail visually impaired. There are however other potential user groups which benefit from a navigation aid such as the PAM-AID. There are many levels in processing sensory information. A person may have relatively good vision but may have problems at a perceptual level. Stroke victims, for instance, may suffer from unilateral neglect. This condition manifests itself in the person being unaware of the space on one side. People suffering from unilateral neglect will collide much more with obstacles in their environment and are more susceptible to injury.

Finally, the device needs to undergo more rigorous long term evaluations in order to improve device functionality and identify possible shortcomings before any commercialisation takes place. Plans are already in place to begin clinical trials with the Department of Veterans Affairs in the United States. The project will involve the testing of five prototypes to be built over a period of two years.

Appendix A

Concept Prototype Questionnaire

Questionnaire PAM-AID User Trials Ireland September 1998

Target participant (P) group: 65+ years, registered visually impaired/blind. Registration: visual acuity is < or = 6/60 in the better eye or the field of vision is limited <20 degrees
Instructions: Tick boxes for 'yes' answers, otherwise leave blank.
Please circle when choices or rating scales are given.
Make clear notes of Ps comments.
Mark Qs which are not applicable (N/A).

Personal Data
Participant's Name/Code________________________________
Age:____________
Gender: **M / F**
Level of Vision:

Blind [ ] Since birth [ ] or [ ] years of age
Partially sighted[ ] Since birth [ ] or [ ] years of age
Sighted [ ]

Place of Residence:

Do you have to use stairs/steps at all? **Yes/Sometimes/No**

Do you need a hearing aid? **Y/N**

Do you have any other disabilities or health problems [e.g. stroke, arthritis]

____

____

Do you use a walking frame or stick to assist you in moving around?

Did you take part in the previous walking aid trials? **Y/N**
If Yes - Trial 1 [ ] Trial 2 [ ]

Evaluation Trials of PAM-AID AP i.e. PASSIVE Version

Researcher: I am going to ask you a few questions about the walking aid while you are walking as I need to find out precisely what you think of this walking aid.

Whilst Walking in Automatic Mode

1. When the walking aid moves forward does it feel heavy, just right or light to push

Heavy [ ] Just right [ ] Light [ ]

Comments: ____

____

2. Does the walking aid jerk at all or is it smooth

Jerky [ ] Smooth [ ]

Comments: ____

____

3. When moving with this walking aid, would you be very worried, moderately worried or not at all worried.

1	2	3	4	5
Not at all worried		Moderately worried		Very worried

Comments ____

____

4. Would you prefer the walking aid to have **brakes**

Brakes [ ] No Brakes [ ]

Why? ____

____

If the answer to question 5 is for a walking aid with **Brakes** ask question 6

If the answer to question 5 is for a walking aid with **No Brakes** move to question 7

Researcher: Ask the P for permission to demonstrate on P's hands the different positions the hands would take for grip and button brakes.

5. Would you prefer the walking aid to have pull up grip brakes or button brakes

Grip Brakes [ ] Button Brakes [ ]

Why? ____

____

Engineer: Change walking aid from Automatic to Manual Mode
Whilst Walking in Manual Mode

6. Do you find directing the walking aid with the handles easy, manageable or difficult.

1	2	3	4	5
Very difficult	Quite difficult	Manage able	Quite easy	Very easy

7 Do you find directing the walking aid to the **left** with the handles easy, manageable or difficult.

1	2	3	4	5
Very difficult	Quite difficult	Manage able	Quite easy	Very easy

8. Do you find directing the walking aid to the **right** with the handles easy, manageable or difficult.

1	2	3	4	5
Very difficult	Quite difficult	Manage able	Quite easy	Very easy

Shared Mode
Researcher: ' The walking aid could be set to take over the steering from you if you were moving into a dangerous situation, for example, approaching a step down or an obstacle'
9. Would you like the walking aid to be able to take over the steering from you.
Yes/Sometimes/No

Cross Comparison
*Researcher: 'You operated the walking aid in different ways, **automatic** where the walking aid guided you gently along the corridor and **manual** where you steered the walking aid yourself.'*
10. Which way did you prefer?

Automatic [ ] Manual [ ]
Comments: ________________________________

____

Handles
11. Can you show me what is the most comfortable way for you to **grip** handles of this walking aid?
Describe: ________________________________

____

12. Did you like or dislike using the handles to steer the walking aid?
Dislike [ ] Like [ ]

Parking

Researcher: 'I will now place your hand on the parking switch so you can park the walking aid.' P presses switch to park the walking aid.

13. Does this walking aid feel **steady** when it is stationery
Steady [ ] Not Steady [ ]

14. Could you use this walking aid to steady yourself when you are going to sit down
Yes/Sometimes/No

Researcher: Ask the P to steer the walking aid towards their usual chair in the sitting room

15. Could you show me how you would use the walking aid to come up to a **seat**
Describe: ____

____

16 Where would you like to **park** the walking aid when you are sitting in your seat
In front of you [ ] Beside you [ ] Outside the room [ ]
Other choice____

______

General

17. Would you say this walking aid is easy of difficult **to learn** to use?

1	2	3	4	5
Very difficult	Quite difficult	Manage able	Quite easy	Very easy

Comments: ____

____

18. Do you think it is easy or difficult **to remember** how to guide this walking aid

1	2	3	4	5
Very difficult	Quite difficult	Manage able	Quite easy	Very easy

Comments: ____

____

19. Overall, how **happy** are you to move around using this walking aid?

1	2	3	4	5
Not at all happy	Not very happy	Moderately happy	Quite happy	Very happy

Comments: ______________________________

20. How **safe** do you feel moving using this walking aid?

1	2	3	4	5
Not at all safe	Not Very safe	Moderately safe	Quite safe	Very safe

Comments: ______________________________

Physical Design/Structure

21. Would you need both hands to support you all the time?

Yes/Sometimes/No

22. Would you like your forearms to rest on the walking frame?

Yes/Sometimes/No

[If Y or sometimes] Would you use this arm rest whilst walking or when stopping for a rest? [or both]

Comments ______________________________

Level of Technology Acceptance

23 How **useful** do think this walking aid will be?

1	2	3	4	5
Not very useful		Moderately useful		Very useful

Comments ______________________________

24. Would **you** be interested in using such a walking aid?

1	2	3	4	5
Not very interested		Moderately interested		Very interested

Comments

Researcher: I would like to take this opportunity to thank you for taking part in this trial.

Appendix B

Long Duration Trial Questionnaire

Evaluation Questionnaire PAM-AID User Trials Ireland April 1999

1. Personal Data (all Ps)

1.1 Participant's Name/Code____________________________________

1.2 Age:________________

1.3 Gender: **M / F**

1.4 Blind [ ] for [ ] years or since birth [ ]
Partially sighted [ ] for [ ] years or since birth [ ]
Sighted [ ]

1.5 Residential Home[ ] i.e. with carers
Own Home [ ] House/Flat
Flat in complex with warden [ ]

1.6 Do they use a hearing aid? **Y/N**

1.7 Do they have any other disabilities or health problems [e.g. stroke, arthritis].
____
____

1.8 Present mobility (i.e. walking aids, assess frailty)
____
____

1.9 Have you ever tried the Pam-Aid rollator before? Y/N

If yes, when?____

2. Walking with PAM-AID rollator

All users will operate PAM-AID rollator initially in Automatic mode. Some users may then operate it in Manual mode.

2.1. Do you find pushing the walking aid easy, manageable or difficult?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

2.2 How well does the walking aid support you?

very well [ ]   about right [ ]   not very well [ ]

2.3 Did you operate PAM-AID in manual mode? Y/N

If yes did you find it easy, manageable or difficult to walk with in manual mode?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

2.4 You have operated the walking aid in different ways. Earlier you pushed PAM-AID and the walking aid guided you by itself. This is the automatic mode. Then you operated it in manual mode where you steered PAM-AID around the obstacles. Which way did you prefer?

Automatic [ ]   Manual [ ]

____

3. Switches

The P should be instructed on the function of all the switches, **automatic/manual**, **parking on/parking off**, and the "turning on the spot" button. The questions relate to the switches in general, but the researcher should note if Ps have any difficulties with specific switches.

3.1 Were the switches easy or difficult to *learn* ?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

3.2 When you were using the switches, did you find them easy, manageable or difficult?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

3.3 Do you think you would find it is easy or difficult to *remember* the function of the switches?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

____

____

3.4 Do you think you would find it is easy or difficult to *remember* how to use the "turning on the spot" button?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

3.5 Did you like or dislike using the switches on the walking aid?

Dislike [ ] Like [ ]

Why?____

____

____

3.6 Did you like or dislike using the "turning on the spot" button to turn the walking aid?

Dislike [ ] Like [ ]

Why?____

____

____

3.7 Is there any way we can improve the switches and/or the "turning on the spot" button?

____

____

____

4. Handle Bars

The P should be instructed on how to use the handlebars. They should walk and experience how to direct PAM-AID forwards, turning left & right and doing a 180° turn.

4.1 Did you find steering the walking easy, manageable or difficult?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

4.2 Did you find the handles easy or difficult to *learn* ?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

4.3 Do you think you would find it easy or difficult to remember how to use the handles?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

4.4 Did you like using the handles to direct the walking aid?

Yes [ ] Sometimes [ ] No [ ]

4.5 How well did the handlebars support you?

very well [ ] about right [ ] not very well [ ]

4.6 Is there any way we can improve the handles?

____

5. Auditory Feedback. Messages:
Ps will hear the auditory feedback whilst walking. If necessary, the researcher should explain the messages and sounds to Ps as they hear them.

5.1 Did you think the messages were useful, not useful or neither?

Useful		Neither	Useful	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

____

5.2 Would you have liked to hear more messages, less messages or was it about right?
More [ ] Less [ ] About right [ ]

5.3 Did you find the messages understandable?
Yes [ ] Sometimes [ ] No [ ]

____

5.4 Do you think the messages are easy to remember, difficult to remember or manageable?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

5.5 Would you like to be able to turn off the messages?
Y [ ] Sometimes [ ] N [ ]

____

6. Parking Mode
If possible, Ps should try and sit in a chair, and stand up from a chair, using PAM-AID for support.

6.1 Does the walking aid feel steady when it is parked?
Yes [ ] No [ ]

____

6.2 Are you able to use the parked walking aid for support when you sit down?
Yes [ ] No [ ]

6.3 Are you able to use the parked walking aid to help you get out of a chair?
Yes [ ] No [ ]

____

7. General

7.1 When you walked with the walking aid, did you feel safe, unsafe or neither?

Unsafe		Neither	Safe	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

7.2 Overall, did you find the walking aid easy to use, difficult to use or manageable?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

7.3 How useful do you think this walking aid will be?

Not Useful		Neither	Useful	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

____

7.4 Would you be interested in using this walking aid?

Interested		Neither	Interested	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

____

Researcher: I would like to take this opportunity to thank you for taking part in this trial.

Appendix C

Manoeuvre Planner Questionnaire

Evaluation Questionnaire
PAM-AID Maneuver Planner
November 2000

1. Personal Data (all Ps)

1.1 Participant's Name/Code____________________________________

1.2 Age:__________________

1.3 Gender: **M / F**

1.4 Blind [ ] for [ ] years <u>or</u> since birth [ ]
Partially sighted [ ] for [ ] years <u>or</u> since birth [ ]
Sighted [ ]

1.5 Residential Home[ ] i.e. with carers
Own Home [ ] House/Flat
Flat in complex with warden [ ]

1.6 Do they use a hearing aid? **Y/N**

1.7 Do they have any other disabilities or health problems [e.g. stroke, arthritis].
____
____

1.8 Present mobility (i.e. walking aids, assess frailty)
____
____

1.9 Have you ever tried the Pam-Aid rollator before? **Y/N**

If yes, when?____

Point out to the user, the switches that he/she requires for the experiment

2. Switches

The P should be instructed on the function of the switches necessary for use with the planner - the **help switch** and the **turn on the spot switch.** The questions relate to the switches in general, but the researcher should note if Ps have any difficulties with specific switches.

2.1 Were the switches easy or difficult to *learn* ?

Difficult — Manageable — Easy

very 1 — quite 2 — 3 — quite 4 — very 5

____

2.2 When you were using the switches, did you find them easy, manageable or difficult?

Difficult — Manageable — Easy

very 1 — quite 2 — 3 — quite 4 — very 5

____

2.3 Do you think you would find it is easy or difficult to *remember* how to use the switches?

Difficult — Manageable — Easy

very 1 — quite 2 — 3 — quite 4 — very 5

____

2.4 Did you like or dislike using the switches on the walking aid?

Dislike [ ]   Like [ ]

Why?____

2.5 Is there any way we can improve the switches?

____

3. Auditory Feedback. Messages:
Ps will hear the auditory feedback whilst using the walker. If necessary, the researcher should explain the messages and sounds to Ps as they hear them.

3.1 Did you think the messages were useful, not useful or neither?

Useful		Neither	Useful	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

____

____

3.2 Would you have liked to hear more messages, less messages or was it about right?
More [ ]   Less [ ]   About right [ ]

3.3 Did you find the messages understandable?
Yes [ ]   Sometimes [ ]   No [ ]

____

____

3.4 Do you think the messages are easy to remember, difficult to remember or manageable?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

____

4. Help Facility (Maneuver Planner)

4.1 Did you find the help facility (the planner) easy to use, difficult to use or manageable?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

____

____

4.2 Did you think the help facility (the planner) was useful, not useful or neither?

Useful		Neither	Useful	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

____

____

____

4.3 Did you feel safe, unsafe or neither using the help facility?

Unsafe		Neither	Safe	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

4.4 Did you find the help facility reliable, unreliable or neither

Unreliable		Neither	Reliable	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

4.5 Can you make any suggestions on how to improve the help facility?

5. General

5.1 When you walked with the walking aid, did you feel safe, unsafe or neither?

Unsafe		Neither	Safe	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

5.2 Overall, did you find the walking aid easy to use, difficult to use or manageable?

Difficult		Manageable	Easy	
very	quite		quite	very
1	**2**	**3**	**4**	**5**

5.3 How useful do you think this walking aid will be?

Not Useful		Neither	Useful	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

5.4 Would you be interested in using this walking aid?

Interested		Neither	Interested	
not at all	not very		quite	very
1	**2**	**3**	**4**	**5**

____

____

____

Researcher: I would like to take this opportunity to thank you for taking part in this trial.

Appendix D

Glossary of Terms

- Closed-loop systems: Systems in which an error signal is fed back into the controller so as to reduce controller error and bring the output of the system to a desired value. The error signal is the difference between the input signal and the feedback signal. The feedback signal may be the output signal itself or a function thereof. Closed-loop control is also referred to as feedback control.

- Configuration: A specification of the position and orientation of the robot with respect to a fixed frame of reference.

- Configuration Space (C-Space): A space which spans the complete set of possible robot configurations. It is common to represent the robot as a point and dilate the obstacles in the configuration space accordingly (C-obstacles).

- Dynamics: That branch of mechanics which treats of the motion of bodies (kinematics) and the action of forces in producing or changing their motion (kinetics).

- Field Robotics: The use of mobile robots in field environments such as work sites and natural terrain, where the robots must safeguard themselves while performing non-repetitive tasks and objective sensing as well as self-navigation in random or dynamic environments. [The Field Robotics Center, CMU]

- Full Width at Half Maximum (FWHM): An expression of the extent of a function, given by the difference between the two extreme values of the independent variable at which the dependent variable is equal to half of its maximum value. FWHM is applied to such phenomena as the duration of pulse waveforms and the spectral width of sources used for optical communications.

- Holonomic: A holonomic system is one in which the number of degrees of freedom are equal to the number of coordinates required to specify the configuration of the system.

- Kinematics: The branch of mechanics concerned with motion without reference to force or mass.

- Omni-directional: The ability of a mobile platform to instantaneously change its direction of motion independent of its current state.

- Open-loop systems: Systems in which the output has not effect on the control action. The output is neither measured nor fed back for comparison with the input signal.

- Proprioception: The ability to sense the position and location and orientation and movement of the body and its parts.

- Service Robotics: The branch of robotics that deals with robots that share human workspaces and relieve or assist humans in the execution of tasks. These robots are autonomous or semi-autonomous and are generally required to work in partially unstructured environments.

- Transfer Function: Function used to characterize the input-output relationships of components or systems that can be described by linear, time-invariant, differential equations.

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