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Context-Aware Shared Control of a Robot Mobility Aid for the Elderly Blind

Abstract

This paper describes the use of a Bayesian network to provide context-aware shared control of a robot mobility aid for the frail blind. The robot mobility aid, PAM-AID, is a "smart walker" that aims to assist the frail and elderly blind to walk safely indoors. The Bayesian network combines user input with high-level information derived from the sensors to provide a context-aware estimate of the user's current navigation goals. This context-aware action selection mechanism facilitates the use of a very simple, low bandwidth user interface, which is critical for the elderly user group. The PAM-AID systems have been evaluated through a series of field trails involving over 30 potential users.

KEY WORDS—mobility aid, robot, visually impaired, Bayesian networks, context aware

1. Introduction

This paper describes a "smart walker" mobile robot designed to provide mobility assistance to the frail elderly visually impaired. This research builds on earlier results (Lacey and Dawson-Howe 1998) by developing a context-aware shared control interface to the robot. The earlier work developed the basic mechanical and control architecture of the robot. This research has concentrated on developing a usable user interface for the elderly. This has been built from general purpose feature detectors, user modeling, and a probabilistic reasoning system.

Because of the sensory and cognitive limitations of the user population, simplicity and robustness were key features of the user interface design. To achieve this simplicity, the number of inputs and outputs was severely constrained. The resulting narrow communication bandwidth between the user and the robot required that the user's needs be explicitly modeled and that user input be interpreted in the context of these needs and the current state of the environment.

The following sections place this research in context both in terms of the user needs being addressed and the related research being conducted in assistive technology.

1.1. Motivation

This research is motivated by the difficulty frail visually impaired people have using conventional mobility aids. The two most common mobility aids are the long cane and the guide dog. The long cane provides a one-stride preview of the ground immediately ahead of the user. Its main limitation is that it does not scan all the space through which the body moves, in particular, overhanging obstacles and holes in the ground are missed. In the case of the frail, the long cane can be used both for support and mobility, but it can be quite heavy and consequently lead to rapid fatigue. Using a long cane and a walking stick in tandem results in both hands being occupied and thus an increased risk of falling. In long-term care facilities, long canes pose a risk of tripping the other residents and this can discourage independent mobility. Before being given a guide dog, a person's visual impairment must be profound, thus preventing them from using residual vision to detect obstacles before the dog avoids them. If this were not the case, the dog would become lazy due to the lack of training reinforcement. Guide dogs walk at a relatively brisk pace and require an active lifestyle to remain fit and healthy. Most elderly visually impaired have some residual vision, and in cases of frailty, a guide dog is not a suitable mobility aid.

Initially, it may seem that this research is focused on a small target user group, i.e., the frail visually impaired. However, demographics show that this is a large and rapidly growing segment of society. At the present time, at least 65% of all visually impaired Europeans are aged 70 and older (Richards 1993); some studies estimate this to be as high as 90% (Bruce, McKennell, and Walker 1991) due to underreporting by the elderly. In the United States, visual impairment affects 18.1%, or 3.6 million people aged 70 and older (Campbell et al. 1999).

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1. www.cs.tcd.ie/PAMAID.

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Demographic trends (Eurostat Press Office 1999) in Europe show that the proportion of people 60 and older will rise from its current level of 21% to 34% by 2050. Even more dramatic will be the change in those aged 80 and older, which will rise from 4% currently to 10% (37 million) by 2050. In the United States, the percentage of people over 65 in the population will increase from its current level of 12.5% (33.5 million) to 20% (69.4 million) by 2030 (U.S. Census Bureau 1995). These surveys also show that the largest increase will be in the number of people aged over 75 in whom disability is most common. The elderly have the majority of chronic and expensive medical conditions (40% or more of the U.S. medical budget). Their increasing numbers allied with the reduction in the number of caregivers means that there will be fewer people to look after an increasing number of disabled and elderly. This has serious implications for the cost and quality of care.

Among the elderly, the coincidence of frailty and blindness is common, preventing the use of typical mobility aids such as guide dogs or long canes. The direct correlation of visual impairment with frailty has been noted in Rubin and Salive (1995) and suggests that both sense of balance and judgment of moving obstacles undergo a progressive deterioration with age. Campbell et al. (1999) report that the visually impaired elderly were twice as likely as the sighted elderly to report difficulty walking (43.3% vs. 20.2%), to have experienced falls in the previous 12 months (31.2% vs. 19.2%), and to have broken a hip (7.1% vs. 4.2%). In addition, the elderly visually impaired are more likely to suffer hypertension (53.7% vs. 43.1%), heart disease (30.2% vs. 19.7%), stroke (17.4% vs. 7.3%), and depression and anxiety (13.3% vs. 7%).

To summarize, the elderly represent the majority of visually impaired people and show a significant deterioration in their activity levels and independence because of the unsuitability of mobility aids such as long canes and guide dogs. The number of people affected is quite large and is growing rapidly as the population ages. The severe impact of visual impairment on the quality of life and health of the elderly has motivated us to develop a mobility aid that specifically addresses their needs.

1.2. Related Research

Farmer (1987) provides a comprehensive review of electronic travel aids (ETAs) for the visually impaired. He notes that even though over 30 distinct devices have been developed since World War II, only 3 have reached extensive field trials and proved their usefulness. The ETAs in question are the Laser Cane (Benjamin 1973), the Pathsounder (Russell 1965), and the Sonicguide (Kay 1996).

There has been much previous work on robotic wheelchairs since the first reported work in 1986 (Madarasz et al. 1986). Since that time, many researchers have used wheelchairs as mobile platforms for robotics research. However, what differentiates such research from assistive technology is that the latter focuses on the needs of users and they participate in the design and evaluation of the systems. Early work on the smart chairs concentrated on providing a user interface for children with cerebral palsy (CP) to the sensor-actuator behaviors embedded within the chair (Craig and Nesbit 1993). More recently, the emphasis has shifted to more complex and adaptive interfaces to the automated elements of the chairs for both users with CP and quadriplegia (Bell 1994; Borgolte et al. 1995; Katevas et al. 1997; Simpson 1997). In the evaluation of these systems, the user interface, the user's comfort, and other psychological factors are as important as the performance of the robotic elements.

In addition to research on smart wheelchairs, researchers have proposed many novel designs for robotic or wearable mobility aids (see Borenstein and Ulrich 1997; Molton et al. 1998; Mori et al. 1992; Shoval, Borenstein, and Koren 1994; Tachi and Komoriya 1985). These aids are aimed at the able-bodied visually impaired. Robotic aids have been proposed to promote walking and exercise among the frail elderly (Dubowsky et al. 2000; Egawa et al. 1999; Engelberger 1989; Nemoto et al. 1998; Schraft, Schaeffer, and May 1998). As of yet, however, few have reported extensive field testing by the elderly or visually impaired.

Also relevant to the design of PAM-AID is research into the physical and cognitive effects of aging as this will affect the design and adoption of the technology by the target user group. Wellford (Birren 1959) reports that the speed and accuracy of elderly people for simple motor tasks is quite good, but this deteriorates rapidly as the task complexity increases. In general, where possible, the elderly shift their concentration from speed to accuracy in an attempt to maximize the use of limited physical resources. Kay (Birren 1959) examines learning and the effects of aging. Short-term memory is very dependent on the speed of perception, and thus a deterioration in perceptual abilities will produce a consequent deterioration in short-term memory. Learning in older people consists of the modification of earlier experiences as opposed to learning from new stimuli. This consists of a process of adapting the previous routine to the new task and features the continuous repetition of small errors. Among the elderly, motivation for learning is much reduced as the acquisition of a new skill may not seem to be worth the effort given the limited life expectancy. Karlsson (1995) notes that *perceived usefulness* rather than usability is the limiting factor in the adoption of new technology by elderly people.

2. Previous Work

The development of the PAM-AID "smart walker" concept began in 1994. Previous publications (Lacey, MacNamara, and Dawson-Howe 1986; Lacey and Dawson-Howe 1998) describe the development of the system and the early evaluations. The system began by fitting a handrail and joystick user interface to a Labmate robot base. This so-called concept prototype is shown in Figure 1. However, initial user trials showed this configuration to be ergonomically incorrect. There were two major design flaws: the handrail did not provide physical support beneath the user's shoulders, and the joystick interface required the user's forearm to be resting on the robot, preventing oscillations due to the relative motion of the user and robot.

The second or "rapid" prototype, shown in Figure 2, improved the ergonomics of the device by fitting a conventional rollator walking aid with robotic elements: motors, sensors, and a user interface. The users input their goal direction by means of switches mounted on the handles of the robot, and user feedback was provided by spoken messages and tones. This system was used to perform the first set of field trials.

In both of the prototypes, the control architecture was based on a set of low-level obstacle avoidance behaviors whose execution was controlled by a scheduler. The scheduler used a finite state machine to determine which behavior to execute. The original controller was a *traded controller* (Sheridan 1992), i.e., control of the robot is traded between the human operator and the automatic navigation system. Thus, the low-level behaviors were either fully automatic, such as wall following, or entirely manual, such as letting the user drive the robot directly. At no stage did the user and controller share the control of the robot. While users found the automatic mode easy to use, it was difficult for them to understand when to switch between the manual and automatic modes. Therefore, a shared control mechanism was developed that was flexible enough to meet different user preferences and dynamic changes in the environment.

Fig. 1. Original "concept" prototype.

Fig. 2. Rapid prototype.

When designing assistive technology (AT), it is important to use the operator's abilities rather than try to replace them. In this research, the visually impaired users already have a good topological map of their environment and PAM-AID provides support by speaking out landmarks, providing warnings of obstacles, and performing local navigation. Consequently, PAM-AID does not use a map of the environment, allowing it to be used in new environments immediately. These requirements indicated that a mechanism was required to interpret the user input in the context of the user's current navigation goals, thus detecting input errors. This paper describes such a mechanism, which has facilitated the design of a very simple, low-bandwidth, user interface.

3. System Design

During the earlier field trials of PAM-AID, users made many recommendations, which have been incorporated into the current design. The mechanical configuration of the robot was improved by customizing a six-wheeled Euroflex electric wheelchair to act as a walker. The design provided a stable platform without the mechanical problems of the earlier modified walker. The center of mass was now above the central drive wheels, ensuring that there was little or no wheel slip or perturbations in the path due to friction in the castors.

The sensors were upgraded from the earlier sonar system to include an Erwin Sick Optik laser range finder and Polaroid sonar sensors. The 180 degree laser range finder provided more accurate results for landmark recognition over the sonar system.

A three-switch user interface allowed the user to indicate a general direction for the robot: forward, left, and right. Voice input was initially integrated into the system in addition to the switch input. However, following field trails it was not used for direction indication due to the difficulty that elderly users have maintaining consistent volume and tone in their speech. The user interface was also complicated by the fact that users sometimes gave erroneous input to the device. This happened when they pushed the wrong switch in error or said the wrong word, e.g., they said “left” when they had intended to say “right.” To distinguish between a valid input and an error, the environmental context for that input was required.

The control software, as shown in Figure 4, was divided into five modules. The risk assessment module provided a collision avoidance behavior to the robot. If objects were detected within specific zones, the robot stopped and provided both a warning and information to the user. The user interface module both gathered user input and provided audio feedback. The feature extraction module extracted corridor and door features from the sensor data. The navigation module used a potential field navigation scheme. The action selection module set the goal points for the navigation module. Within the action selection module, the environmental features were combined with user input using a Bayesian network. This produced a decision that selected the level of user feedback and the goal for the navigation module. The following sections will describe the feature extraction and action selection systems in more detail.

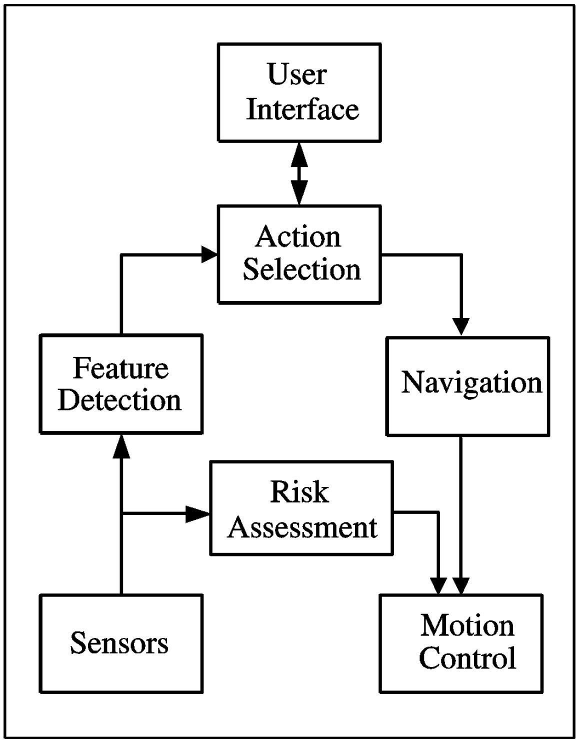

Fig. 4. Software architecture.

Fig. 3. PAM-AID prototype.

4. Corridor Classification

The aim of the corridor classification system was to provide the reasoning system with sufficient information to classify the robot’s environment as straight corridor, a left-turn junction, and so on. The Range Weighted Hough Transform (RWHT) (Forsberg, Larsson, and Wernersson 1995) was used to extract the range and bearing of straight-line features in the laser data in the presence of obstacles. Doors were classified as gaps in the line features of approximately 900 mm. The line features were then classified according to their length, orientation, and location with respect to the robot and were passed to a Bayesian network to perform the classification. A Bayesian network classification scheme was chosen for two reasons: first, the classification decisions could be verified by analyzing the network nodes, and second, the results of the classification step were to be passed to a Bayesian network influence diagram, which performed the context-aware decision making.

The Bayesian network classification network fused the features to classify the corridor as one of six types. The different corridor types are shown in Figure 5. A greater number of corridor classifications could have been used, e.g., left and right turn, opening on left, right, ahead, and so on. The types shown represent the most common types and were deemed sufficient for the evaluation of the adaptive control system.

The corridors were classified according to how the presence of certain wall features corresponded with each corridor type. The network was able to perform a valid classification even in the absence of some features or in the presence of sensor error. The corridor classification subnetwork is shown in Figure 6. The six feature types represented the size and type of line features around the robot. The lines were assumed to be walls that were labeled with respect to the orientation of the robot—wall ahead, wall left, and wall right—and walls oriented approximately perpendicular to the path of the robot—perp wall ahead, perp wall left, and perp wall right. The nodes scaled the feature strength as being weak, medium, strong, and certain in proportion with feature length. The top-most layer classified the features into one of six corridor types.

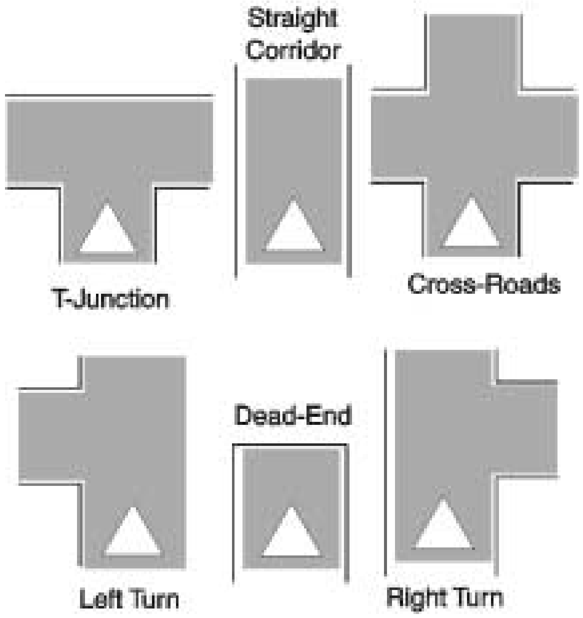

Fig. 5. Corridor types.

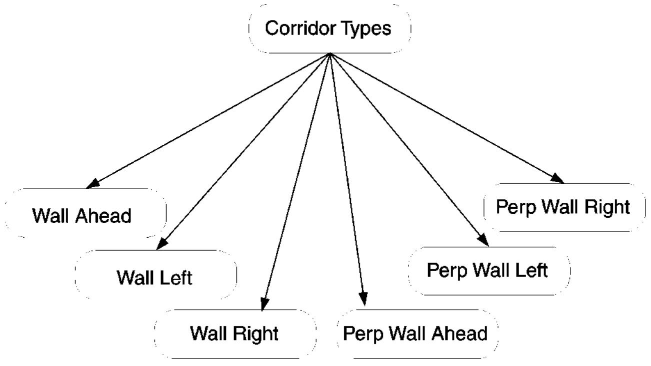

Fig. 6. Corridor classification Bayesian network.

Training was required to arrive at realistic prior probabilities for the nodes and was achieved using the *Learning from Cases* feature of Netica.[1] This supervised Bayesian learning algorithm learns the causal probability tables for those nodes for which a finding has been declared and the value of all its parents defined. Netica uses the concept of experience numbers to represent the confidence it has in its probabilities. They represent the number of cases the network has seen that correspond to the configuration of the parent node.

For each new case, the configuration of the parent is specified and the corresponding experience number is incremented according to the degree of learning, normally one, thus Experience$'$ $=$ Experience $+$ Degree. Using the concept of experience, the values in the causal probability tables (CPT) (which represent the relationships between the nodes in the network) are updated. Within any one CPT, the probability value consistent with the parent configuration (CP in the formula) is incremented according to the following equation:

$$CP' = \frac{CP \times \text{Experience} + \text{Degree}}{\text{Experience}'}.$$

Those values inconsistent with the parent configuration (IP in the formula) are changed according to the following equation:

$$IP' = \frac{IP \times \text{Experience}}{\text{Experience}'}.$$

The above learning algorithm was used to construct the CPT values from 100 examples of each corridor type; therefore, the number of instances of corridor types in the training environment had no bearing on the outcome. The laser scans were taken from a variety of different positions to ensure robustness and generalization. When the training was completed, the corridor classification was tested using live data. It was found to detect the presence of dead ends and T-junctions up to 5 meters away. Because the training data were not exactly symmetric, left turns were slightly more likely than right turns. Such anomalies are to be expected in any system trained with real sensor data. However, Bayesian networks can be tuned to remove these anomalies using sensitivity analysis.

Sensitivity analysis provides a mechanism of measuring the impact that instantiating one node in the network has on the probability of another. Some nodes will have little or no effect on each other while others may be strongly linked. There are several measures that can be used; one is Shannon's Measure of Mutual Information (Shannon and Weaver 1949), which

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2. www.norsys.com.

assumes that the uncertainty in a variable Z, with probability density function $P(z)$, can be represented by its entropy:

$$H(z) = -\sum_{z} P(z)\log P(z).$$

In the corridor classification network, the average residual uncertainty remaining in "Corridor Classify" (CC), given that "WallAhead" (WA) has been instantiated, can be written

$$H(CC \mid WA) = -\sum_{cc}\sum_{wa} P(cc \mid wa)\log P(cc \mid wa).$$

If the value of $H(CC \mid WA)$ is subtracted from the original uncertainty in Corridor Classify prior to the instantiation of WallAhead, we get the uncertainty-reducing potential of WallAhead. This is called Shannon's Mutual Information and is given by

$$I(CC, WA) = -\sum_{cc}\sum_{wa} P(cc \mid wa)\log \frac{P(cc, wa)}{P(cc)P(wa)}.$$

$I(CC, WA)$ is a nonnegative number that is zero in the case of CC and WA being mutually independent.

In the case of the corridor classification network, the mutual information and the percentage entropy reduction of instantiating each of the nodes is shown in Table 1. This shows that the most valuable information, in terms of discriminating the corridor class, was the presence of a wall perpendicular to the robot's path positioned directly ahead, followed by the presence of perpendicular walls to the left or right. Sensitivity analysis is a useful feature for diagnosing the behavior of the network and determining the relative importance of the features in the network such as the priors and the relative strengths of links between nodes encoded by the CPTs. Thus, Table 1 explains the sensitivity of the network to dead ends and T-junctions. The values in these CPTs were then modified to reduce their sensitivity. The effect of each change was measured by further sensitivity analysis and observing the resulting corridor classification.

The state of the network, i.e., which nodes are instantiated or not, affects the sensitivity analysis by changing the node that would contribute most to reducing the current uncertainty.

Table 1. Sensitivity of "Corridor Classify" Due to a Finding at Another Node

Node	Mutual Info.	Entropy Reduction (%)
PerpWallAhead	0.48259	20.6
PerpWallLeft	0.31641	13.5
PerpWallRight	0.31641	13.5
WallAhead	0.17010	7.26
WallRight	0.06043	2.58
WallLeft	0.03679	1.57

This feature can be used to control the focus of attention of the system and schedule costly sensor-processing routines as in Kristensen (1996). However, in this application, feature extraction is performed in one step and the cost of selecting between sensor-processing routines of variable precision is not justified by greater efficiency.

These priors of the Corridor Classify node (see Fig. 6) were influenced by a number of factors: most significant, it provided a weighting scheme to balance the sensitivity of the different classifications against each other, e.g., T-junctions and dead ends could be detected up to 5 meters away. While in some robotics systems this may be a useful feature, the users of PAM-AID had to be presented with each landmark feature description at a consistent distance of 2 meters to use this information for navigation. To provide this consistency, the prior probability of T-junctions and dead ends was suppressed in favor of straight corridors and left and right turns. Another feature of the system that provided consistent landmark feedback to the user was that the certainty of the classification had to be 70% and be maintained for three cycles of the sensor system before the landmark message was provided to the user.

5. Adaptive Control

Bayesian networks have been used to combine multiple information sources in robotics (Simpson 1997; Wachsmuth et al. 1999) and have been used to model user intentions in application software (Horvitz et al. 1998). However, this research demonstrates the combination of user input with sensor data to effect context-aware goal selection for a mobile service robot.

Figure 7 shows the high-level architecture of the Bayesian network influence diagram that performs the reasoning. The user's goals are modeled as goal directions to the navigation system, e.g., to turn left or to enter a door to the left. The probability of these goals is influenced by the probabilities in their parent nodes: Corridor Types, Door Classify, and User Input. These probabilities are fused to produce a context-aware estimate of the user's goals (in Corridor Constraint and Door Constraint), e.g., what robot action the user wants to take next. An estimate of the conflict between user input and the current context is estimated in the Conflict Detect node. The prior probabilities and the relationships between the nodes were determined by heuristics and tuned following sensitivity analysis.

The nodes Corridor Constraint and Door Constraint produce a distribution across a set of robot actions, e.g., move forward, take the door on the left, and so on. To select the most appropriate robot action, these likelihoods are scaled according to the utility assigned to each action (user action utilities). The utilities are a weighting scheme that encodes the commonsense preferences, e.g., the utility of the "Go Forward" robot action is high for the Corridor Constraint state

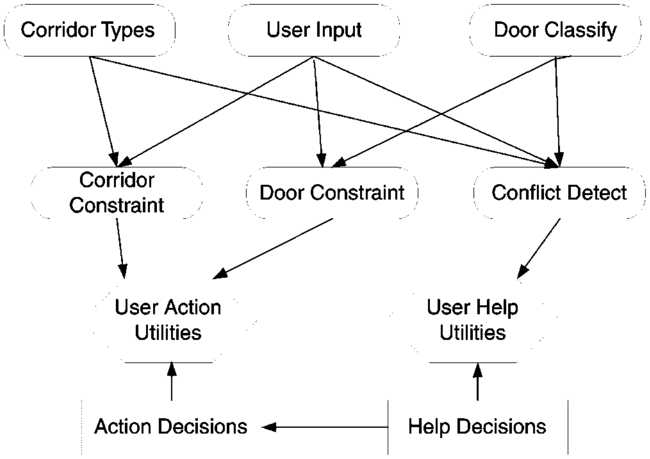

Fig. 7. Action selection influence diagram.

Go Forward, and other robot actions have low utility. The Action Decision node then selects the action with the highest expected utility, where expected utility is the likelihood multiplied by utility. The final action selected for execution will also be influenced by the decision of the help system.

The help system is driven by the level of conflict between the user input and the current context as measured by the Conflict Detect node. This measurement of conflict produces a decision on the part of the help system as to whether or not to intervene in the execution of the current action. The User Help Utilities provide a weighting scheme that favors user input or robot control in the final decision making. In the presence of conflict, the system either executes its estimate of the user's goal or it stops, informs the user of the conflict, and waits for the next valid input. The utilities can be scaled to intervene only in case of extreme conflict or to intervene even when there is minor conflict. Thus, user's preferences with respect to the level of help provided were modeled as a set of utilities. Thus, when the user's inputs were out of context, e.g., pressed the right turn switch when a right turn was impossible, this was noted as a conflict and, depending on the user's help utilities, this event was ignored or the robot stopped and provided information.

The operation of the network is illustrated by the graph in Figure 8. This sequence is taken from one of the user trials, which will be described in the next section. The sequence covers approximately 7 seconds in which the participant, a very frail partially sighted woman of 84, performs a right turn. At point A on the graph, the robot detected a T-junction, stopped the robot, and produced the help message. At point B, the user understood the help message and stopped pressing the forward switch. At point C, the user pressed the right switch and the robot began turning. At point D, the turn was completed, the robot stopped, and the user let go of the right switch. For this trial, the utilities were set so that the robot favored a "stop-and-ask" approach over an approach that would assume the user's intentions.

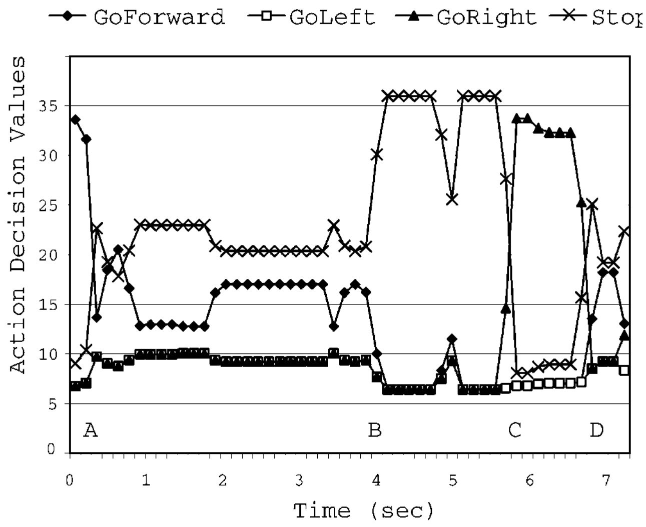

Fig. 8. Execution trace for 7 seconds.

6. System Evaluations

This research followed the *Interactive Evaluation* strategy advocated by Engelhardt and Edwards (1992) for the development of assistive technology. Therefore, during the development of the robot mobility aid, three major field trials were carried out, in seven locations in the United Kingdom and Ireland. In all, 30 participants used the devices, ranging in age from 55 to 94, with the average age of 82. During the trials, a wide range of design ideas were evaluated and the users were encouraged to suggest alternatives and improvements.

The final trial of the system took place in St. Mary's Nursing Home for visually impaired women, Dublin, Ireland, April 12-16, 1999. The five participants were aged 67 to 95 with a mean age of 82. All participants were partially sighted; the severity of vision loss ranged from residual vision in one eye to profound visual impairment. The mobility of the participants ranged from good independent mobility to being ordinarily wheelchair bound. The severity of both visual and mobility impairments was correlated roughly with the ages of the participants.

The number of participants necessary to identify usability problems in a device is a topic of great importance. Several studies (Nielsen 1994; Virzi 1992) show that 80% of usability problems will be identified by three to five participants, with each further participant adding less and less new information. It is not possible to perform long or exhaustive trials with elderly people due to their physical and cognitive limitations. Individual differences in the participant's physical and sensory capabilities prevented the use of a separate test group and control groups.

The aim of the trial was to determine the user's subjective assessment of the ease of use of the adaptive context-aware interface compared to the manual interface. In manual control, the user interface was directly coupled to the goal settings for the navigation module. Thus, out of context, input could not be detected. In adaptive mode, the user input was first processed by the context-aware Bayesian network. The participants were asked to execute a path, shown in Figure 9, using the device in both modes. The order in which the modes were presented to participants was alternated to remove bias. A questionnaire was administered after participants had tested the device in both modes.

6.1. Manual Control

The manual switch interface allowed participants to set the goal points for a potential field obstacle avoidance algorithm. The switches used were **forward, left**, and **right**. In all modes, releasing a switch stopped the robot. This level of control required the participant to determine the heading for the robot based on residual vision and/or on the information provided by the spoken messages. Participants were asked to rate their responses to questions on a 5-point Likert-type scale, where 1 is *bad* and 5 is *good*. The mean ratings for manual control are summarized in Table 2.

6.2. Adaptive Control

The adaptive control mode, described in Section 5, was used by all the participants. The experimenter explained the function of the mode and the meaning of the warning/explanation voice messages. The robot used the Bayesian network to determine the current context and process the user input accordingly. If the user input was deemed “out of context,” the robot issued a warning message and stopped. Examples of out-of-context input were if the **Left** or **Right** switch was pressed while in a straight corridor or if the **Forward** switch was pressed while at a T-junction.

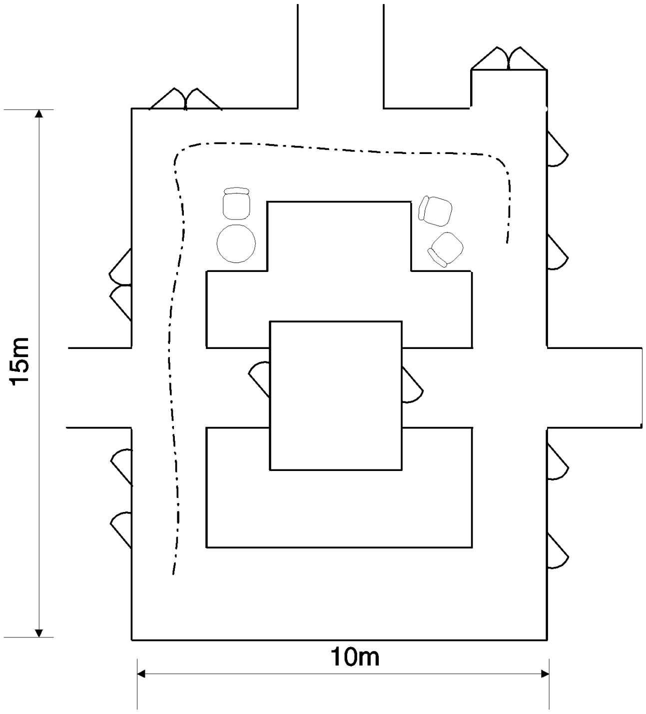

Fig. 9. Map of system evaluations.

Table 2. Manual Goal Setting

	Mean	Std Dev
Overall Usability	3.8	0.4
Learnability	4.2	0.74
Ease of remembering	4.2	0.4

Table 3. Adaptive Goal Setting

	Mean	Std Dev
Adaptive Helpful?	4	0.6
Safer in Adaptive?	4	0.5

To compare the adaptive mode with the manual mode, participants were asked if they found it helpful when the device noticed erroneous input. Participants gave a positive mean rating of 4 (i.e., quite helpful), with a standard deviation of 0.6. This question prompted a lot of discussion. The participants with good partial vision found it less useful than those with poor vision. The participants with good residual vision commented that the robot did not take the “shortest path,” i.e., did not cut wide corners as they would have done themselves and prevented them from doing so manually by disabling the switches. Participants with poor vision found that the adaptive mode was particularly useful when turning at the end of corridors. Participants with poor vision lose their bearings very quickly when turning. The adaptive mode stopped the robot from turning when it was pointing straight down the new corridor, thereby preventing overshoot. In the words of one participant, there was “no chance of turning too far” in adaptive control mode.

Participants were also asked if they felt safer using the device in adaptive mode over the manual mode. They gave a mean rating of 4 (i.e., quite a bit safer) with a standard deviation of 0.5. Many of the comments were that both modes were safe. Those participants with severe visual impairment commented that they found it significantly safer.

Some participants said that in adaptive mode they paid more attention to the voice messages, as they now contained more information. This attention was most noticeable when the robot issued a warning and stopped until a safe input was given. A frequent comment was that while participants found the robot safer in adaptive mode, they did not like giving up more control to the robot. Some stated that this was due to nervousness and that they would get used to it over time. Those with some residual vision said they did not need the help and therefore did not want it.

6.3. Landmark Voice Messages

Voice messages were used as the primary mode of feedback. Feature messages describing the landmarks were produced every 6 seconds while the landmark remained unchanged. However, if a new landmark appeared, the appropriate message was produced immediately. Table 4 gives the mean ratings and standard deviations of questions directed at assessing the utility, content, and comprehension of the voice messages.

The most frequent comment was that the messages were too quiet. The corridors were periodically very noisy; radios playing loudly, metal trolleys being pushed around, and loud conversations sometimes drowned out the voice messages from the PC. The more visually impaired participants also mentioned that they would like the naming of specific places such as the dining room, smoking room, and so on. This last point was echoed by the caregivers and the National Council for the Blind representatives who attended the trials.

6.4. General Acceptability

The participants were asked a number of general questions to rate the overall acceptability and usefulness of the device. They were also asked to make suggestions with regard to the long-term use of the device in the home. Table 5 summarizes the results of questions with regard to the overall safety, usability, and utility of the device in general and the utility of the device to them personally.

The device was regarded as quite safe and very easy to use. Participants felt that it would be quite useful in general for other people in the residential care facility. When asked if they would use the device themselves, the average statement was that they would find it quite useful. However, if the youngest and most mobile participant is eliminated, the mean statement rose to very useful.[2] This is because the youngest participant felt that she did not need a mobility aid and could not foresee herself needing one. Her response may reflect the fact that she was the youngest and most mobile of the participants but also she alone was visually impaired since birth and had developed a range of strategies to compensate for her disability. The other participants had lost their vision relatively recently (median 3.4 years) and did not have a lifetime of experience of coping with visual impairment.

Table 4. Voice Message Ratings

	Mean	Std Dev
Utility	3.8	0.4
Content	5	0
Comprehension	3.67	0.7

Table 5. General Ratings

	Mean	Std Dev
Safety	4.5	0.6
Usability	4.6	0.5
General Utility	4.2	0.4
Personal Utility	4(4.5)	1.1(0.57)
Physical Support	5	0
Switch Usability	4.3	0.4

Participants made a range of suggestions relating to the overall use of the device. The most common suggestion was that the device should identify specific places in the residential care facility: dining room, smoking room, bedrooms, and so on. Some participants wanted the device to tell them where to go and what button to press. The frailest participants wanted a seat on the device so that they could rest if they got tired.

A voice interface was mentioned as the most desirable interaction method. In particular, this was mentioned in the context of requesting the device to navigate from point to point in the residential care facility.

6.5. Recommendations

The robot mobility aid was used in the St. Mary's Nursing Home for the Visually Impaired for 5 days (April 12 to 16, 1999). The residents, caregivers, and National Council for the Blind staff discussed it at length for the week, resulting in three major recommendations.

6.5.1. Device Customization

The first major recommendation was that the device should be customized for individuals. The customization should include the type and position of input device. Attention should be paid to arthritis and mild hemiplegia, both of which are common among the elderly. The adaptive assistance mode was useful for the severely visually impaired but less so for the partially sighted. During the trials, the utility measures were not customized for each user but were set at an "interventionist" level to highlight the difference between the two modes. However, this possibility exists as a means of reducing the level and type of help provided by the device to meet the need for user customization. The caregivers see the device as being useful as a shared resource between a number of residents. All users would have their own handles, which a caregiver could change as needed. Other user preferences should be easily selected by the caregivers during the setup phase.

6.5.2. Integration with Building

Many of the participants and caregivers mentioned the need for naming particular places within the building, such as the

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3. See numbers in parentheses in Table 5.

dining room and chapel, while the device was moving along. Additionally, some participants recommended point-to-point navigation as a desirable feature of the device. Others requested that the device give them specific directions rather than lead them from point to point. This level of integration could be achieved in the first instance by using maps of the building and performing accurate robot localization. To date, this approach has been avoided due to the feeling that the device should be able to operate in any residential setting with minimal customization. It may be possible to integrate the PAM-AID with the Talking Signs[3] system to provide spoken messages naming parts of the building.

6.5.3. Integration with Daily Living Routine

The 5-day period of the user trial allowed users and caregivers to explore the concept of having an intelligent mobility aid in some depth. Life in a residential care facility is highly structured with all activities following a set routine. By the end of the week, structured mobility had become part of the routine of the residents, with each of them taking turns on the device. Previously, the use of the aid had been seen as an "on-request" service provided to residents. During the trial, residents queued up to use the device and guarded their time on the device jealously. Part of this behavior was due to the novelty of the device and the attention accorded to the user. Whatever their initial motivation, the device quickly became "part of the day" for residents. This social dynamic may wane if the device became commonplace or may work to reject the device if not introduced sensitively. Viewed positively, the device allowed the development of a structured exercise regime that did not require constant attendance by a caregiver.

7. Conclusions and Future Work

This research has grown to include an alternative mechanical design for PAM-AID that has passive traction and a force-sensing user interface (MacNamara and Lacey 2000). The passive system is preferred by individuals whose frailty is a result of balance problems rather than weight bearing. The advantage of the passive system is its intrinsic safety and lower system cost. However, because of the lack of powered traction, the passive system is incapable of autonomous activity, which may limit its overall flexibility. The PAM-AID system as described here is best suited to those with more severe frailty as the robot moves at a steady speed and does not represent a load to be pushed. The powered traction also opens up the possibility of autonomous behavior being incorporated into the final system.

Currently, both robot designs act as simple mobility aids: no task-specific behavior has been included in the design such as point-to-point navigation, docking with beds and chairs, or fetch-and-carry tasks. Of particular interest is the integration of the PAM-AID within a smart building so that several PAM-AIDs may be shared by a large number of users (O'Hart and Foster 1999) and interact with other automated elements of the building. It is envisaged that these types of tasks will be included in the next versions of PAM-AID.

We aim to commercialize the PAM-AID system[4] and are collaborating with medical research partners to validate the clinical effectiveness of PAM-AID on user activity levels and fitness. Where PAM-AID is being used daily by users, we are investigating its role as a focus for health monitoring and health maintenance. Exercise programs could be specified and a user's progress monitored via wearable sensors for heart rate and blood pressure. We are also investigating the clinical role in user training posttrauma and in the assessment of gait patterns following brain injury.

To date, we have only considered the controlled and familiar environments of an independent living center or residential home. Ultimately, we would like to tackle more dynamic public spaces such as shopping centers, museums, and ultimately the outdoor streetscape. However, a number of major technical challenges must be solved prior to achieving this, not the least of which is the development of a totally reliable and cost-effective range sensor to map the terrain in front of the robot as well as detecting holes in the ground and descending stairs.

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[4] www.talkingsigns.com.

[5] www.vartry.com.

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