An Assistive Robotic Agent for Pedestrian Mobility

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ABSTRACT

The goal of this project is to develop a pedestrian mobility aid for the elderly. In order for this type of assistive technology to be useful and accepted by its intended user community, it must enhance the abilities of users, not replace them. This leads to an agent architecture in which the agent must operate without hindering the user's ability to take direct action when they choose. In other words, the agent cannot simply be a proxy for the user's actions. The agent must select its own goals based on observations of its user's actions. This is crucial not only because users may have diminished capacity to explain their actions to an agent, but because the ability of the agent to correctly interpret the user's goals is tied to its ability to act while still allowing the user to "feel in control". We present a mobility aid, i.e. a wheeled walker, which varies its goals and level of activity based on an estimation of its user's intentions. The assistive agent often takes no action, allowing the user to be fully in control. When the ease or safety of the user's travel is threatened, the agent attempts to influence the user's motion based on its belief in the user's goal. By varying the degree of autonomy, the walker can adjust to the user as their abilities change from day to day, or hour to hour. This prevents the walker from "trying to do too much", allowing the user to feel as if they are in control and not being "lead".

Keywords

Assistive technology, smart walker, robotics, control systems.

1. INTRODUCTION

The world's elderly population is increasing dramatically. In the US, there are more than 34.8 million people over the age of 65. Furthermore, in only 30 years, this number will more than double to 70 million [11]. In Japan, the nation with the highest percentage of seniors on earth, it is estimated that 1 in 5 people will be seniors within 10 years [18]. At the same time the costs of health care, including caring for the elderly, could rise from its current $1.3 trillion to over $4.0 trillion [4]. If robotic technology could be used to enable the elderly to remain independent, significant costs would be saved and the quality of life improved for these people. The attainable cost savings are significant: for every single month that we delay the transition of the elderly population into nursing homes, the US economy saves over $2 billion [2].

Many seniors have mobility impairments that cause a downward trend in their quality of life. Lack of independence and exercise can have dramatic results. Walkers are used more than any mobility aid except the cane [16]. This paper describes our work in designing an assistive robotic agent based on a wheeled walkers, or rollator, to aid in pedestrian mobility of the elderly [20]. We describe a shared control strategy that enables an elderly user and their walker to collaborate on movement, increasing the ease and safety of the user's travels.

2. ASSISTIVE ROBOTIC AGENTS

The types of agents we are interested in are designed to enhance their user's capabilities, not replace them. Users have some basic physical and mental abilities to perform a task, but may perform it inefficiently or unsafely. The assistive robot then, allows the user to perform actions, possibly modifying these to help meet the user's goals. Assistive technologies designed to replace lost functionality are not covered by this work. For example, in the mobility domain, wheelchairs may meet the mobility needs of our target audience, but they deny capable users the ability to walk.

Assistive agents cannot be merely executives for their users, receiving high-level commands, but performing detailed actions autonomously. They must allow the user to directly interact with the world when the user desires. This is important in allowing the user to use the abilities they possess and retain the feeling of control. The assistive agent should monitor the user's interaction with the world and help when the user needs it. The abilities of the elderly (the target group for this work) vary from day to day and hour to hour. This means the agent must observe the behavior of the user to determine the user's current capabilities and how it can assist. We should emphasize that we are interested in assistive technologies that help users accomplish tasks in the physical world. Other interesting agent technologies, such as those that increase accessibility of computers and the internet will undoubtedly have different control systems than the agent presented here.

Assistive robotic agents are different from conventional autonomous robots as well as other agent technologies. There are two ways in which the "autonomy" of an assistive agent varies from that of a fully autonomous agent. First, although the assistive agent has goals, it selects them based on the perceived goals of its user. The agent's goals are altered, as the user's goals/needs change. The agent presented in this work has the goals of keeping its user from hitting obstacles or falling down while helping them move to their destination. This involves helping the user maneuver appropriately in situations that may be difficult or

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dangerous. This, in turn, involves determining where the user wishes to go in a manner that is not cognitively overburdening for the user.

The second differentiating characteristic of assistive robotic agents is that they may neither act truly autonomously, nor continuously. Keeping the user involved in the physical action with which the assistive agent is helping is a primary goal of this work. Therefore, assistive robot agents should be incapable of taking direct action. Rather they should always require the user to perform some action, the outcome of which may be affected by the actions of the assistive agent. In this sense, the assistive agent provides the feeling of control to the user by never performing an action that was not initiated by a user action.

In addition, many states of the assistive agent's belief, world, and goals will cause the agent to take no action, thus allowing the user to directly interact with the world. For fully autonomous agents, time spent taking no action would typically be considered wasted time. For assistive agents however, this time is simply when the user does not need assistance. Since the assistive agent seeks to augment the user's capabilities and not replace them, it need only take action when it will be beneficial to the user (e.g. when the user is having difficulty or is in danger).

As with other agents, the interface between the user and the agent is of primary importance to the success of an assistive robotic agent. Users may have diminished ability to explain their goals to the agent and so it may be forced to discern user intent from watching user action. This is complicated by the fact that users may have diminished ability to perform actions, and therefore there may be a difference between what the user does and what they mean to do. Since any assistive agent will not always identify their user's goals correctly, a feedback control system is necessary. The interface then, must provide a natural and intuitive means for the user to express both their goals and their satisfaction with the agent's actions.

The key questions for the design of any assistive robotic agent then are how to model the user's intent, how to determine the appropriate action given that intent and how to develop an appropriate interface. We will address these questions for our agent in the next section.

3. ASSISTIVE ROBOTIC WALKER DESIGN

The purpose of the assistive robotic walker is to improve the ease and safety of the pedestrian travels of elderly users. This means preventing collisions with obstacles and preventing falls that might result from sudden changes in the walking surface (cliffs). Walker frames are typically wide to provide enough balance support for their user. However, this makes them difficult to maneuver in cluttered environments. Intelligent motion control that assisted the user with the task of fine steering control would be a great benefit. For this task, we have constructed an assistive agent in the form of a pedestrian mobility assistant for the elderly. This robotic device is based on a commercially available, 3-wheeled frame or "rollator" (see Figure 1). The frame has been augmented with sonar and IR sensors, as well as a motor system to steer the front wheel. The manual brakes have also been replaced with an automated braking system. The walker can sense the user's steering input via sensors in the handles that detect the difference in force on the two handles.

Figure 1. The Assistive Robotic Walker

Essentially, the walker has the control system pictured in Figure 2. Both the agent and the user provide control input to the frame and both the agent and the user observe the results of actions taken. Note that the user's sense of control in this paradigm is based partially on the passive nature of the robot. The walker can never move without the (implicit) consent of the user and so moves at the user's own pace. This is an important difference with other shared control systems because the control is not hierarchical. The user continually attempts to achieve their goals (perhaps inaccurately) and the assistive agent tries to adapt its goals to the user's so that it can help. The key is the physical grounding of this fusion between human and agent control in the walker frame itself. The frame can only follow one command and so differences between the actual and expected motion of the frame will be perceived by both user and agent. The user will understand that the agent detected danger and the agent will determine that the user did not agree with its selected motion.

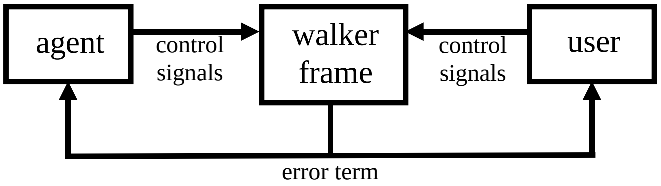

Figure 2. Walker Control Architecture

The walker has been designed to be passive, cooperative and submissive. The walker is passive because it can only adjust the facing direction of its front wheel, i.e. it can steer [5][17]. However, it has no "forward" drive motors and so relies on the user for motive force. This allows the walker to move at the user's pace and provides for the user's feeling of control. Since the user depends on the walker for balance, a passive robotic device like the walker removes much of the difficult control problem associated with an active drive system that tries to move toward a goal and provide support for the user. The user simply moves the device at a natural pace that preserves their balance.

The walker is cooperative and submissive in the way it interacts with its user. These characteristics define the way in which this assistive agent regulates its level of autonomy. The walker is cooperative because it attempts to infer the user's path and uses this inference to decide how to avoid any obstacles in the user's path. The walker is submissive because it monitors the user to see if they are resisting the actions (steering/braking) selected by the walker. If they are, the movements are adjusted. This cycle continues until the user agrees with the motion (i.e. does not resist it) or manually over-rides it. This interaction forms the basis of the feedback loop between user and agent. The remainder of this section discusses how the user's goals are inferred and the actions the walker takes.

3.1 User Path Inference

Inferring the user's path is important when steering and/or braking the walker. This information allows the walker to know how and when to maneuver for obstacle/cliff avoidance. In general, there may be many ways to avoid an obstacle. By using knowledge of the user's goal, the assistive agent can maneuver the frame in a manner that is most comfortable (and unnoticed) by the user. The agent attempts to infer the user's intended path using a combination of sensory data, user input, history and its own position and orientation. Data from the walker's sonar and IR sensors is fused into a probabilistic representation similar to [19][15]. As mentioned above, the walker is quiescent most of the time. This means that the user is normally in control and so the walker's position and orientation within its local map is a good indication of the direction that the user is heading. This forms the basis for the path inference algorithm, which proceeds as follows. At each time step, the walker estimates the probability that the user is traveling on each of the possible arcs from its current position[1] by assigning a weight to each path. Although it is possible to rotate the walker in place and thus proceed along a straight line to any point, users do not operate the rollator this way. The walker is typically moved in a non-holonomic style in which all motions are a combination of translation and rotation, i.e. an arc.

Paths are weighted first by the orientation of the walker. Paths whose translation component is in the same direction as the walker's sensors indicate it is facing (either forward or backward) are given more weight than those paths with the opposite component. When the walker is stopped, paths in front of the walker receive more weight (though this will be effected by other factors). Next, paths are weighted by length. The length of a path is the distance that the walker could travel along that arc without its frame impacting an obstacle or cliff. Initially, longer paths are more heavily weighted. Finally, paths are weighted by a history of the user's steering input. Averaging the user's steering commands over a long period may reveal their general heading, but would give an inaccurate result when the user changes direction or is maneuvering in a tight space (where large directional changes may take place for short periods of time). Instead, we add additional weight to the paths that are similar to the arc followed in the last time step. The relative weight added for length or history is approximately the same while the weight added for paths with the correct translation direction is an order of magnitude more.

Weight can also be subtracted based on the user's steering input. Sensors in the walker's handles allow it to monitor the difference in force placed on both handles. When the user pushes with more force on one handle (left or right), the walker will turn in the opposite direction. The difference in force will determine the relative amount of translation vs. rotation with a larger difference corresponding to more rotation and less translation. Equal force on both handles will move the walker straight forward or backward (which direction can be determined by the walker's wheel encoders). When the agent is actively steering the front wheel, there will inevitably be situations in which the path chosen by the agent does not correspond to the path desired by the user. When the two differ sufficiently, it effects the user's perception of the walker and they feel as if they are not in control of it. The handle sensors allow the agent to detect such conditions because they occur when the user's steering input differs sufficiently from the direction that the agent is orienting the front wheel. When this happens, the agent reduces the weight of paths near the direction of the wheel orientation and increases the weight of paths around the direction indicated by the user.

After the path weights have been determined, the walker may act based on the most likely path. However, there will not necessarily be a clear maximum. If the user were standing in a large room free of obstacles, all paths in front of the walker would be equally likely. If there is no maximum likelihood path, the walker cannot use that information in decide on its action. It may however, still perform some basic safety actions as discussed below.

3.2 Action Selection

The actions taken by the agent are always to help the user avoid collisions or falls. Therefore, it only acts in the presence of danger and otherwise leaves the user in control. However, the nature of the action will be dependent on the path that the agent believes the user is on. The agent has a set of tolerances for how close it can move to obstacles or cliffs before taking action. These tolerances are depicted in Figure 3.

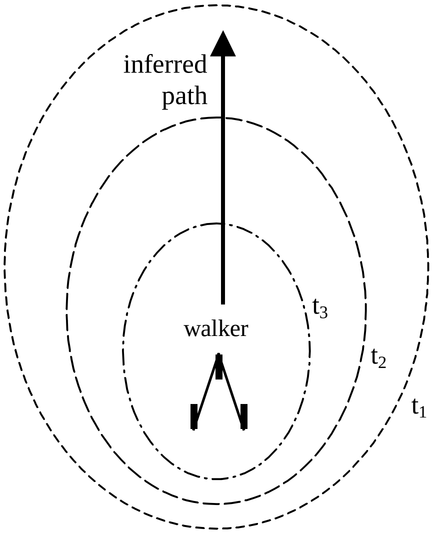

Figure 3. Walker Steering and Braking Tolerances

If the walker is within t_1 of an obstacle, then the agent will take evasive steering action. If the walker is within t_2, it is too close to steer effectively without impacting its user's balance and the agent will activate the brakes, slowing proportionately to the distance to the obstacle. If the walker is within t_3 of an obstacle, the agent engages the brakes fully, halting the walker's motion in the minimum time. The brakes will also not disengage until explicitly

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[1] There are, of course, an infinite number of arcs from any position and so some discretization is necessary.

over-ridden by the user. In normal operation, the walker may never get within t_3 of an obstacle because when it begins to slow (due to being within t_2), the user will react. If the walker gets within t_3, it is likely to be because the user is in a dangerous situation of which they are unaware or not able to correct appropriately. Since the user's safety ultimately depends on their own abilities and not the agent's, it is important to fix the walker's position until the user has had a chance to locate the problem and decide on the right corrective action.

The boundary between t_1 and t_2 depends on the user. A walker must provide balance support to its user at all times. It is therefore critical that the walker's actual motion does not significantly diverge from the user's intended motion, as this may lead to a fall. The boundary between t_1 and t_2 then is determined by the maximum turning rate that a user can tolerate.

The exact values of t_1, t_2 and t_3 are not fixed, but rather are affected by two factors. The first is relative to the path on which the user is believed to be traveling. The length of a path affects its weight, but the width of a path affects the values of the action tolerances. The width of a path at a point is the distance between obstacles (or cliffs) on either side of the path along a segment perpendicular to the path at that point. Narrower paths require smaller tolerances if the user is going to fit through them.

The second factor is user resistance to the agent's decisions. A basic conflict arises when the agent's goal is to prevent the user from hitting obstacles and the user's goal is to roll up to the kitchen sink. In some systems, these modes are referred to as obstacle avoidance and docking [13]. The agent must be able to re-prioritize goals in response to conflict. Recent work has shown the value of auto-regressive time series forecasting in allowing agents to re-prioritize their goals in response to environmental factors [10]. In this domain, the agent initially has high values for the tolerances, meaning the walker comfortably avoids obstacle. If the user resists a particular steering motion, the weights of the various paths will change and possibly make a short path into an obstacle be the most likely. The walker will then decrease the values of the tolerances, allowing a closer approach. This could continue in stages, with the agent continuing to reduce its tolerances each time the user fights a corrective action. However, we believe that multiple stages will be too confusing to the user and involve too much fighting with the walker. Instead, a single stage reduction is used that causes the tolerances to shrink to some minimum value. If the user still desires to get closer, they need to step out of the walker.

4. RELATED WORK

The PAM-AID project [12][14] developed an assistive walker for the elderly blind. This device allowed its users to receive exercise when their abilities might otherwise allow. Their walker takes a more active role in guiding its user than our assistive robotic agent because the user's visual acuity is typically very limited. The work also focuses on corridor following since exercise is the prime motivation. This project is investigating what can be done with passive devices in home environments. The PAMM project [6] also seeks to create an assistive walker. While development of the actual walker is ongoing, a "smart cane" has been developed. This is also an active device that guides its user based on directional forces placed on the cane. They use an admittance controller [1] to provide obstacle avoidance while letting forces placed on the cane determine which obstacle-free path to take. However, this control system proved difficult to operate in cluttered environments. Our path weighting scheme should allow the walker to determine the user's intentions using a natural interface, the walker frame itself. It is hoped that the fact that the walker is passive, steered as any other rollator, and only acts in certain situations will make the user feel comfortable and in control. It is possible that the agent's corrective actions will not even be noticed if they are along the user's intended path, since this is what the user "meant to do".

The passive steer-only joint of the walker that relies on the user for propulsion is similar to other passive robots, e.g. Cobots [5] and PADyC [17]. These systems use the same concept to allow a human operator to provide coarse motions and timing, while the joints of a robotic apparatus provide the fine-grained motion. Passive robotic systems have been used for automobile assembly and surgery, but are only beginning to be looked at in the assistive technology field. We believe passive systems will have a large impact.

Various other mobility aids have been developed, mostly for powered wheelchairs [8][9][13][21] (an exception being the GuideCane [3]). While all these devices face similar issues as our walker, wheelchairs are essentially mobile robots ridden by their user. Their users do not rely on them for balance in the same manner that a walker user relies on their walker's frame and so different control algorithms can be used. They also provide a form of hierarchical control in which the mobility aid performs detailed actions based on higher-level user specification. This is different than our agent in which the user must always be involved in the actions of the mobility aid.

The agent/user interaction models discussed here are not new [7]. We have applied them to the domains of assistive technology and robotics and have found that these domains lead to interesting issues in terms of user ability and user satisfaction.

5. DISCUSSION

Assistive robotic agents can provide invaluable assistance to their users. The connection between the agent and the user is the key to this. In the case of our walker, this connection is made through the walker frame itself. We argue that this interface meets the goals of assistive technology interfaces in that it does not place any additional cognitive burden on the user during use or training. No additional controls are added to the frame so that any user that can operate a traditional walker can operate the assistive robotic walker. Of particular interest is how users express their satisfaction with the agent's control decisions and how that expression influences the actions of the agent. This feedback is crucial for user approval of the walker.

In our system, the user expresses their lack of approval with the agent by resisting its steering decisions. The assistive agent guesses the user's intent and tries to move the walker appropriately. This guess, act, then check for approval paradigm prevents the user from having to explicitly confirm every action of the agent, but inevitably leads to situations where the user's desire does not mesh with the agent's actions. The agent's model of the human must be based on not only its observations of the human's actions, but also on their resistance to any control commands it has attempted. This leads to the question of trust. Is the user resisting the agent's actions because the agent has misinterpreted their goals or because they simply do not agree with the action the agent is taking to accomplish those goals? The more trust the user has in the agent, the more they may be willing to allow the agent to steer because they believe that the agent has correctly divined their goal. But, the user can never develop so much trust in the agent that stop acting, since the agent requires user interaction with the world to continually refine its notion of user goals. Achieving the right level of trust is a focus of this project.

Ultimately, the success of an assistive robotic agent can be measured by the satisfaction of its user. This, in turn, will be a function of how well the device helps the user accomplish their goals and how it "feels" doing it. We believe that our agent is most successful when the user is least aware of its presence. When the user has to resist motions of the walker, they are reminded that there is another agent in the control system. The more that the agent is able to correctly model the user's intent and thus modify their actions appropriately, the more useful it will be. The actual movement of the walker frame can differ only so much from the user's expectations; otherwise their balance will be compromised. The agent can go unnoticed by making minimal changes to user actions. Since elderly users may have difficulty translating their goals into correct moment-to-moment actions, it is hoped that small modifications to the user's actions will not only allow the agent to remain invisible, but will make the user feel more empowered. This is because the walker frame will be doing what they *meant* it to do, even if that is not what their motor commands told it to do.

6. ACKNOWLEDGMENTS

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