ADAPTIVE SHARED CONTROL SYSTEM

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Abstract

A control system to aid mobility is presented that is intended to assist living independently and that provides physical guidance. The system has two levels: a human machine interface and an adaptive shared controller.

Keywords: adaptive, control, drive, shared.

Introduction

Some people require assistance with guidance. If disabilities require constant attention, a skilled nursing facility may be a solution but costs are higher and quality of life can be reduced (Burton, 1997). It is cost-effective to keep the people out of nursing homes if possible (Yu et al, 2003). There are social and economical benefits to delaying the transition using robotic technology. Smart assistive technology can offer potential solutions and there is a growing interest in developing intelligent assistive devices. The PAM-AID (Lacey and Dawson-Howe, 1998) is a robotic mobility aid that provides some physical support and obstacle avoidance. The Care-O-bot (Schraft et al., 1998; and H¨agele, 2001) and the Nursebot (Baltus et al., 2000) are personal service robots developed for the elderly and disabled. The Care-O-Bot is intended to aid mobility, do household jobs, and provide communication and entertainment functions. The Nursebot project has focused on human machine interface methods, tele-presence via the Internet, speech interface, and face tracking. A device called Power-Assisted Walking Support System has been developed at Hitachi to help support elderly people standing up from bed, walking around, and sitting down (Nemoto et al., 1999). A device called a Personal Mobility Aid is being developed at University of Virginia (Wasson et al., 2001). It is modified from a standard three-wheeled walker by fitting a steering motor, adding encoders for dead reckoning, and adding laser and IR sensors for obstacle detection. User interface is critical for all these devices.

The design must take into consideration the user's characteristics. The users of mobility aids generally have direct physical interaction with the system for support. A key requirement is that the interface should be able to adapt to users with different levels of physical and mental functionality. The interface should provide reliable bilateral communication between the user and the machine to ensure safety. It should also provide a natural feel for the user and be easy for the user to learn to use. Researchers have studied various forms of interfaces. The joystick is widely used for robotic wheelchairs (Levine, 1999; Lankenau and Rofer, 2001). However, a joystick can cause oscillatory motion when users walk with a device (Lacey and MacNamara, 2000). Switches and buttons can be used to select directions or control modes, but they are limited by their discrete nature (Lacey and MacNamara, 2000). They could also increase the mental workload and cause confusion and frustration. Touch screens have also been implemented as an interface (Baltus et al., 2000; Schraft et al., 1998) and a pointer device was described in Sanders & Tewkesbury (2009). Using voice communication as human machine interface is another area of research (Yu et al, 2003). These can become effective high-level command and bilateral communication tools, but they cannot serve as continuous control interface. For cooperative robotic devices in industrial applications, where the human operator and the machine have direct physical interaction, force sensing and the related force control strategies have been used (Al-Jarrah and Zheng, 1997). Using force signals directly to generate motion can result in unstable motion due to the fluctuation of the signals (Yu et al, 2003). This problem has been encountered with Care-O-bot project (Graf and H¨agele, 2001).

This paper considers admittance based control using a force/torque sensor to provide a natural and intuitive interface for elderly users in a similar way to that used by Yu et al (2003). A challenge is how to allocate control between a user and the machine. A shared control system integrates the best capabilities of both the human and the machine. Humans are best at high level cognitive tasks such as object identification, error handling and recovery, use of heuristics and common sense in the presence of uncertainty (Yu et al, 2003). On the other hand, machines have high mechanical and computational power, and good accuracy. Work has been done in the shared autonomy and cooperative control for tele-operations, space, and aviation systems (Sheridan, 1992). Researchers are developing shared control strategies for assistive devices. Various methods of shared control design of power wheelchairs are An Adaptive Shared Control System for an Intelligent Mobility Aid for the Elderly (Cooper, 1995). In these control strategies, there are a few preset discrete behaviour modes using fuzzy logic or probabilistic models, such as wall following, passing doorways and obstacle avoidance. The shared control methods are used to select from one of them based on the obstacle sensor information and user input. Methods have also been developed to make the shared control system adaptive to different tasks and situations for a wheelchair (Levine et al., 1999; Simpson and Levine, 1999). These few behaviour modes can limit the freedom of a user. Research has been completed to investigate control of robotic and tele-robotic systems (Sanders 2009a and 2009b) and other vehicles (Sanders, 2008). However, it is important to identify the capabilities of the operator, particularly when the user may have diminished mental and physical capabilities (Yu et al, 2003).

Aid for Mobility.

Some systems were developed in the Field and Space Robotics Laboratory at MIT to assist the elderly in assisted living facilities and delay their transition to nursing homes (Dubowsky et al., 1997; Godding, 1999; Spenko, 2001; D'Arrigo, 2001). Others have been described by the author (Sanders, 2009a and 2009 b).These have been tested in simulated living facilities including, structured indoor environments with random obstacles such as furniture and people and flat and relatively hard floor or ramps of less than 5 degrees. A joystick has served as the main user interface as they are still the most common interfaces for wheelchairs. An admittance-based controller integrates the user input signals with signals from an obstacle avoidance sensor in order to control the system. The system can communicate via a wireless link with a central computer in order to receive up-dated planning information and to provide information on the location of the user. Location can be determined from a CCD camera which reads passive signposts placed on the ceiling but more often the system is used with only the obstacle avoidance system. This paper focuses on control and in particular the joystick user interface. This interface should be able to determine the intent of the user even in the presence of the user's confusion. The controller gives the user as much control as possible, but ensures user safety by adjusting control authority. It must be noted that the development of control algorithms for human machine systems is less analytical and precise than that for completely determined systems and autonomous control. The development and evaluation of the control system depended on experimental work carried out at the University of Portsmouth. The controller had two levels. A lower level considered user interaction control based on the admittance based control methodology (Yu et al, 2003). The higher level was the adaptive shared controller for the control allocation between the user and the machine. These two levels are described.

Admittance Control

A six-axis force/torque sensor was attached to the joystick and used as the main control input interface. Through it the user had continuous control of the system. The force/torque sensor signals were interpreted for motion control by using an admittance controller (Durfee et al., 1991). The admittance model emulated a dynamic system and gave a “feeling” as if the user was interacting with the system. The admittance of the modelled dynamic system was defined as a transfer function with the user's forces and torques, $F(s)$, as input and the velocities, $V(s)$, as the output. It is expressed as:

$$G(s) = V(s) / F(s) \qquad (1)$$

The reciprocal transfer function was called impedance, which has been the basis for the widely used concept of impedance control. The response was obtained by solving the dynamic equations in real time, and solving the inverse kinematics of the physical system to get the desired actuator velocity. The admittance control approach allowed the dynamics to be set, subject to limitations of actuator power, servo control bandwidth, and computation limitations. Models with fast dynamics required higher bandwidth and fast sampling time for the control system and complex models required more computation power. However, these do not appear to be significant issues for devices for slow moving people. Users interacted through the force / torque sensor on the joystick. Signals from the force/torque sensor in the joystick contained user's intention. Signals from the force sensor first went through a transformation so that the driving forces and the support force at the joystick were extracted. The support force, which pointed downward, was not used to generate motion directly, but was used for stability analysis and as a condition to start or stop the motion. It was found in field experiments that a few users generated unintended forces which were coupled with the driving forces (Sanders 2009a and 2009b). For example, some users initially generated an unintentional twisting torque at the joystick. However, with some practice they often developed good control. Driving forces were also filtered before the admittance model to eliminate high frequency noise. The admittance model could be changed for each individual user. The states of the system, such as velocities, were monitored and used to change the dynamic model so that the control was variable. The joystick had two main degrees of freedom, one for forward motion in the Y direction, and the other for rotation around the Z direction but the joystick was omni-directional and had 3 degrees of freedom. Hence admittance models with two and three DOF mass-damper systems were implemented. A linear 2 DOF mass-damper model was defined as:

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

(Yu et al, 2003).

In the forward direction, the system emulated a plant of a mass M and damping B. With F as the user input force in the forward direction and V as the system response in the same direction, the transfer function of the system was:

$$G(s) = V(s) / F(s) = 1 / (Ms + B) \qquad (3)$$

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

$$v(t) = F / B\ (1 - e^{-t/\hat{o}}) \qquad (4)$$

Where ô was the time constant defined by ô = M/B. The steady state velocity of the system was Vss = F/B.

Experiments

A challenge was determining the appropriate model (M and B), choosing a metric to evaluate the performance of the model, and optimizing the dynamics to minimize operator effort. These questions were addressed with experiments with users through field trials using the environments described in Sanders (2009a and 2009b). Experiments were conducted. First, a series of tests were conducted to evaluate the general usability of admittance control. The admittance model had M and B as 14 Kg and 40 Ns/m respectively. The wheelchair moved at an average speed of about 0.25 m/s. The average driving force (Fy in the forward direction) was about 12 N. Because the mass-damper model also acted as a low pass filter, high frequency noise due to shock and vibration from the floor and the hand tremor of the user was reduced. The driving force signal had some high frequency noise, but speed was smooth with a lower frequency variation. It also showed that the forward driving force and the downward support force were in concert. To study the acceptance of the system and to help select the values of the admittance model (M and B), questionnaire surveys were also used in the field experiments as a qualitative measure. Users were asked to drive freely and compare the system with and without assistance. Issues with ease of control, how heavy it felt to drive, ease of learning, physical support, and overall acceptance as a mobility aid was evaluated using a five point scale.

The result of the tests by a group of eight volunteer users were positive. The model used for these tests had a mass M of 14 Kg and a damping B of 60 Ns/m. Although average ratings were relatively high on every issue, the variations suggested that different users required different system parameters. To determine the effects of M and B, nine models with different mass and damping combinations were tested. Values of M used were 2.5, 5, and 10 Kg, and the values of B were 10, 20, 30 Ns/m. From the tests, the effects of different mass and damping combinations were identified. For models with small mass and damping, the motion was oscillatory because the model was too responsive. For models with small mass and high damping, which had small time constants, the motion was also oscillatory, this time due to high frequency noise. For models with large mass and small damping, the motion was difficult to control as the inertia was too large; users felt that they were dragged along when they wanted to stop. When both mass and damping were too high, the system was too heavy.

There existed a range for both B and M that was acceptable; but the exact value for both should be tuned to each individual's needs. It was also found that users have different requirements during different phases of motion therefore, the model should be less responsive at the start, with higher mass and damping. When a user wanted to stop or slow down, the system should be able to stop immediately to avoid dragging the user forward. A model with bigger mass would require bigger damping to slow down. It might also need the user to apply backward force to slow down; causing oscillatory motion that was uncomfortable and dangerous for a user. That meant it was necessary for the model to have higher damping and smaller mass when a user wanted to stop. Users always wanted the system to appear light (meaning small driving forces) when moving slowly at a constant speed. From the steady state response of the model, it was known that the force required to achieve a certain steady state velocity depended on the damping alone. Although it was necessary to let the user to feel some force so that they felt that they were in control, the force should be kept small to prevent fatigue. That meant the damping should be kept small. The fixed parameter model could not satisfy the seemingly contradictory requirements for different phases of motion of the system. It could be seen that the damping had a more important role to play. An admittance model with velocity-dependent damping was designed. The damping of the model was given by:

$$b = bm - (bm - b0) / Vm\,|V| \qquad (5)$$

Where bm is the maximum damping, b0 is the minimum damping, V is the speed, and Vm is the maximum speed allowed. With the variable model, the system initially responded to user input slowly due to the high mass and damping at low speed. However, when the user moved at a relatively high speed, the user needed less driving force due to the reduced damping and the speed did not fluctuate as much because of the high mass. When the user needed to stop, the system stopped quickly as the damping increased, so that the user did not feel drag. This model was implemented and tested by 10 volunteer users. Users all agreed that the variable model was easier to drive.

Adaptive Shared Control

The objective of the shared control design was to give a user as much control as possible while still ensuring adequate performance. For assistive devices, the controller was used to assist the user rather than replace the user in performing a task. However, users could have limited physical and cognitive capability or irrational behaviour. When a user demonstrated that they could not operate safely, more control was given to the computer. An adaptive shared control framework was proposed by Yu et al (2003) that was similar to the structure of a classical adaptive controller (Narendra and Annaswamy, 1989). The system had a planner that generated an ideal path based on the task and knowledge of the environment. The system determined its location in the environment by identifying sign posts with a CCD camera (Dubowsky, 2000). The computer controller generated a virtual force input based on the pre-planned and actual trajectories. The user gave inputs to the system through a force/torque sensor connected to a joystick. The two control inputs to the shared controller had an associated gain, Kcomputer and Khuman, respectively. These gains reflected the control authority of the computer and the human. These gains were changed by the adaptation law. The adaptation law first computed a performance index J based on a metric ä, which was a measure of how well the user was performing. It then adjusted the two gains to minimize J . The output of the shared controller was fed to the admittance-based control, which in turn generated low-level control commands for the physical system. The different parts of the algorithm are discussed below. The first step was to determine an ideal path and the velocity and acceleration profiles of the system along that path. The pre-planned trajectory needed to take into account that the system had limited sensing capabilities and could not know the entire environment explicitly. The main function of the computer controller was to guide the user back to the pre-planned trajectory when the user deviated from it and when the shared controller deemed it necessary based on the performance evaluation. However, one important issue was that the controller should not force a human user to the trajectory. The computer limited the control forces based on the capability of the user. Another function of the computer controller is to act as a safety watchdog, even when there is no pre-planned path. For example, when the system was under free driving by its user, the computer also monitored the user's speed, location, stability and conditions. When there was an imminent danger, the computer acted by limiting the speed or guiding the user to a safe path. The user's performance metric needed to include such factors as proximity to obstacles, deviation from the trajectory, excessive or high frequency oscillation about a path, and tip over margins (Papadopoulos and Rey, 1996). The chosen metric here is a quadratic function combining all the factors considered and is given as:

$$\begin{aligned} \ddot{a} = \quad & k1(x)^2 + k2(dx/dt)^2 + k3(dx^2/dt)^2 \\ & + k4(dis)^2 + k5(S)^2 + \cdots \qquad (6) \end{aligned}$$

Where:

ki = weighting factors x = $\text{position}_{\text{ideal}} - \text{position}_{\text{actual}}$
dx/dt = $\text{velocity}_{\text{ideal}} - \text{velocity}_{\text{actual}}$
$dx^2/dt^2 = \text{acceleration}_{\text{ideal}} - \text{acceleration}_{\text{actual}}$
dis = distance to obstacles
S = f (stability criteria)

The value of the weighting factors needed to be adjusted for a given population and environment. The proposed adaptive shared control algorithm had the control law:

$$F = FcK_{\text{computer}} + FhK_{\text{human}} \qquad (7)$$

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

The adaptation law adjusted the gain K_{computer}. First, at time ti, a performance index J (i) was calculated, which was an integral of the performance metric ä:

$$J(i) = \sum_{k=1}^{i} \delta(k) e^{-\lambda(i-k)\Delta t} \qquad (8)$$

In this method, to avoid an abrupt change, the control authority was adjusted based on the performance history of the user. However, past data should carry less weight on the adaptation, thus an exponential forgetting factor was introduced. The parameter had units of 1/s. With a smaller (or longer forgetting term), the control authority was changed more gradually. With the performance index J (i), the gain for the computer control was calculated using the following adaptation law:

$$K_{computer}(i) = 1 - e^{-\hat{a}J(i)} \qquad (9)$$

Where â is the gain used together with ë to adjust the behaviour of the adaptation. Under this adaptation law, the controller gains, $K_{computer}$ and K_{human} were adapted to the user's capability measured by the performance metric. These gains determined the balance of the control authority that the human had compared to the pre-planned trajectory, or how responsive the system was to a user. Depending on the relative control allocation, a system could be said to be in manual, shared, or autonomous control mode. However, due to the high sampling frequency these modes were essentially continuous rather than discrete, and the adjustment of control authority was automatic.

Experiments with Adaptive Shared Control

Validation of the shared control design depended largely on experimental work with real users. The field trials for the adaptive shared control were conducted at the University of Portsmouth. In general, users had good navigation skills. Tests were conducted in various environments (as described in Sanders 2009a and 2009b). The test path had a maximum length of 35 meters passing through up to two standard doorways that were 3 feet wide, running a long corridor that was 6.5 feet wide, to the research laboratory area. In the corridor, three different paths were selected, the one along the centre was designed to make the task easier, and the other two were closer to the wall and designed to make the task tougher as the user has to avoid the wall. These paths were not marked on the floor during the tests. A group of six users participated in the experiments. The age of these volunteers ranged from 18 - 25. Each user tested the wheelchair under three different control modes: free driving, full computer control, and adaptive shared control. Different forgetting factors were also tested to show its effects on the control performance. Before the test with the adaptive shared control, each user was asked to drive freely along the path for three to five times. These tests were intended to get the user familiar with the systems and to get all users the same exposure. Each user then tested the systems under free driving, adaptive shared control, and full computer control along the path. The order of the control modes tested with each user was different in order to counterbalance the effects of learning. The users were not told which control mode they were using. The performance metrics used in these tests are the deviation from the path and the distance to the wall.

In some parts of the trajectory, the computer control gain decreased as long as the user was not getting too close to a wall. To compare the performance of the user under different control modes, the distances to the walls and deviations from the path of a user under the three tests were recorded. Under free control, the users deviated from the path as much as 0.35 meters. The user frequently got close to the wall along the corridor. Under the adaptive shared control, the deviation was smaller and the user could stay on the path and maintain a safe distance from the wall along the corridor. Although performance was improved, a user could not notice the difference from the free driving. It was seen that performance under the full computer control was also good. However, most of the users did not like the full computer control and complained that the system had a mind of its own. This was because the controller did not allow a user to deviate from a path even when they were far from a wall.

With short forgetting terms (bigger ë value), the computer control gain changed quickly. The controller behaved like a reactive obstacle avoidance algorithm. With longer forgetting terms, the control was not returned to the user immediately after the computer gained more control; therefore, performance improved. The value of the forgetting factor should be different for each user or situation. Longer forgetting factors could be used for users with less capability or in difficult situations. These experiments demonstrated the effectiveness of the adaptive shared control.

In practical applications the control modes were continuous rather than discrete, and the switching of control was based on a user's performance.

Conclusions

A system has been developed to assist a user in controlling a wheelchair. The objective was to enable users and the system to work cooperatively. The two most important aspects of this design were the human machine interaction control and the adaptive shared control. With the force/torque sensor in a joystick as the main human machine interface, an admittance-based human machine interaction control was developed. The admittance control allowed a user to have a natural and intuitive control. The control could be tuned to individual characteristics by changing the model defined in software. Through field experiments with various parameters of the model, the effects the model parameters were identified.

Based on the experimental study, an adaptive admittance model with velocity-dependent damping was also tested and it demonstrated smoother motion and increased user comfort. In addition, an adaptive shared control framework was developed to allocate control authority between the system and a user. The control allocation was based on the demonstrated performance of the user. The control design was also validated in field trials.

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