Stability Margin Monitoring in Steering-Controlled Intelligent Walkers for the Elderly

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Abstract

This paper emphasizes the importance of assessing stability index for steering-controlled three-wheeled walkers. The paper describes a stability computation model that can be used to generate a reference input to the intelligent shared-control algorithm. The model can be used to evaluate the instantaneous stability margin of the walker-user system. This knowledge of the online stability of the walker will enable the shared controller to intelligently decide on the most appropriate time for the activation of the control to minimize the likelihood of jeopardizing the system stability as a result of the system's control actions, and possibly prevent falls due to control actions. The results of a stability computation model, based on the force-angle stability measure, are presented for different walker-assisted navigational scenarios including: walking straight, making soft turns, making sharp turns, and control fighting. The results showed that assisted steering enhanced the user's stability when the user's and the walker's intents were aligned. However, the results also indicated that a conflict between the user's intent and the walker's control actions (or walker's intent) in so called intelligent walkers could jeopardize the stability of the walker-user system, and hence that of the walker's user.

Keywords: Intelligent Walker, Shared Control, Stability Margin, Force-Angle Stability

Introduction

One of the most important factors in quality of life for the elderly is their ability to move about independently. Not only is mobility crucial for performing the activities of daily living (ADLs), but for maintaining fitness and vitality. Lack of independence and exercise can lead to a vicious cycle. Decreased mobility due to a perceived lack of safety can cause muscular atrophy and a loss of the feeling of empowerment (both of which contribute to further decreased mobility).

An intelligent pedestrian mobility aide is being developed to help the frail elders negotiate obstacles in indoor environment. The primary goal of this work is to augment a user's ability to walk, not replace it. In this sense, we are seeking to help those who can and want to walk perform this task more safely and easily. As the world's elderly population rises (the US Senior population will double over the next 30 years (Kramarow et al. 1999)) and the cost of healthcare skyrockets (to $4 trillion over the same period (Ciole and Trusko 1999)), robotic mobility aides will increase in importance. The shared control framework of our walker is based on the notions of passive robotics and user intent. Passive Robotics means that the walker's control system is not thought to be continuously active nor can it provide motive force. It is capable of controlling only the angle of the walker's front wheel and it will only attempt to bias that angle in response to concerns about the ease and the safety of the user's movement. When no such concerns arise, the control system is completely passive, allowing the user the full control of the walker.

In the recent few years, various research institutes across the world have come up with designs for intelligent mobility aids for the elderly (Hans, Graf, and Schraft, 2002), (Morris et al. 2003a), (Dubowsky, Genot, and Godding 2002), (MacNamara and Lacey 2000), (Morris et al. 2003b). PAMM (Graf, Hans, and Schraft 2004) was designed to accommodate multiple modes of operation with the flexibility to vary the degree of the autonomy of the system. The PAM-AID (MacNamara and Lacey 2000), developed by University of Trinity - Dublin, also allows two modes of operation – manual and assistive. In the assistive mode, the walker assumes control of the steering and navigates around obstacles. The robotic walker (Morris et al. 2003b), developed at the Carnegie Mellon University – USA, uses a haptic interface to determine the navigational intent of the user. Though the authors claim that their design improved the stability, the paper did not present any stability computation model that was used to quantitatively assess the improvement in stability. The paper also did not discuss stability jeopardizing situations involved in shared control. The intelligent walkers employing shared control usually assist the user in obstacle avoidance and in some cases provide additional features like providing simple directions to target locations (Morris et al. 2003b), guidance to destinations in a known structured environment (MacNamara and Lacey 2000), and execution of complex manipulation tasks (Graf, Hans, and Schraft 2004) where the user input is either graphical or speech commands.

Walkers that are based on shared control architecture are generally passive during navigation and engage active control only in certain cases. However, control actions in intelligent walkers may jeopardize the stability of the walker-user system, and hence that of the users under certain conditions. This is especially true in the case of abrupt control actions, or when the user attempts to resist the computer generated control action if the computer failed to correctly identify/interpret the user's intent. Nonetheless, not much research has been done on assessing/ monitoring the stability of the walker platform, to potentially modify the walker's control action to restore walker-user system's stability.

This paper builds on previous research performed at the University of Virginia in using instrumented wheeled walkers to develop a human-machine shared-control system that assists users by increasing the safety and speed of their daily travel (Wasson et al. 2003), (Wasson et al. 2001a), (Wasson et al. 2001b). This walker gauges the user intent using a haptic interface that derives the forces and moments applied by the user on the two handles of the walker. Our walker is cooperative and submissive in the way it interacts with the user. The walker is cooperative because it attempts to infer the user's path and uses this inference to decide on 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 action 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 overrides it.

Since walkers are prescribed for the elderly to improve their stability, the control design should avoid any situation that may jeopardize stability during the navigation. This paper presents a stability computation model, based on the force-angle stability measure. The paper presents the variations of the computed stability index for different walker-assisted navigational scenarios including: walking straight, making soft turns, making sharp turns, and control fighting.

Methodology

Walker design

The walker is a standard Sprint three-wheel rollator, from Invacare, OH, USA, augmented with two 6-DoF load cells US120-160 from ATI Industrial Automation, NC, USA. The walker's handles were sawn and the sensors were mounted in-line between the handles and the walker's frame, as shown in Figure 1. The sensors provide the load/moment transfers between the walker and the user.

Figure 1. The Instrumented Walker

This haptic interface serves as a medium of interaction between the user and the walker and helps the walker in predicting the user intent at any point of the navigation. The walker's environment is sensed by an infrared sensor that produces a radial depth map (Alwan et al. 2005). Histogram in Motion Mapping (HIMM) (Borenstein and Koren 1991) is adopted for map-building in this research for its ability of fast local map building (Murphy 2000) due to its computational efficiency. The walker is designed on shared control system architecture, shown in Figure 2, in which the user has the control authority for the navigation of the walker and the control from the walker will be activated only when necessary. The user's behavior and intent is detected using a physics-based math model derived for the walker (Huang and Sheth 2004).

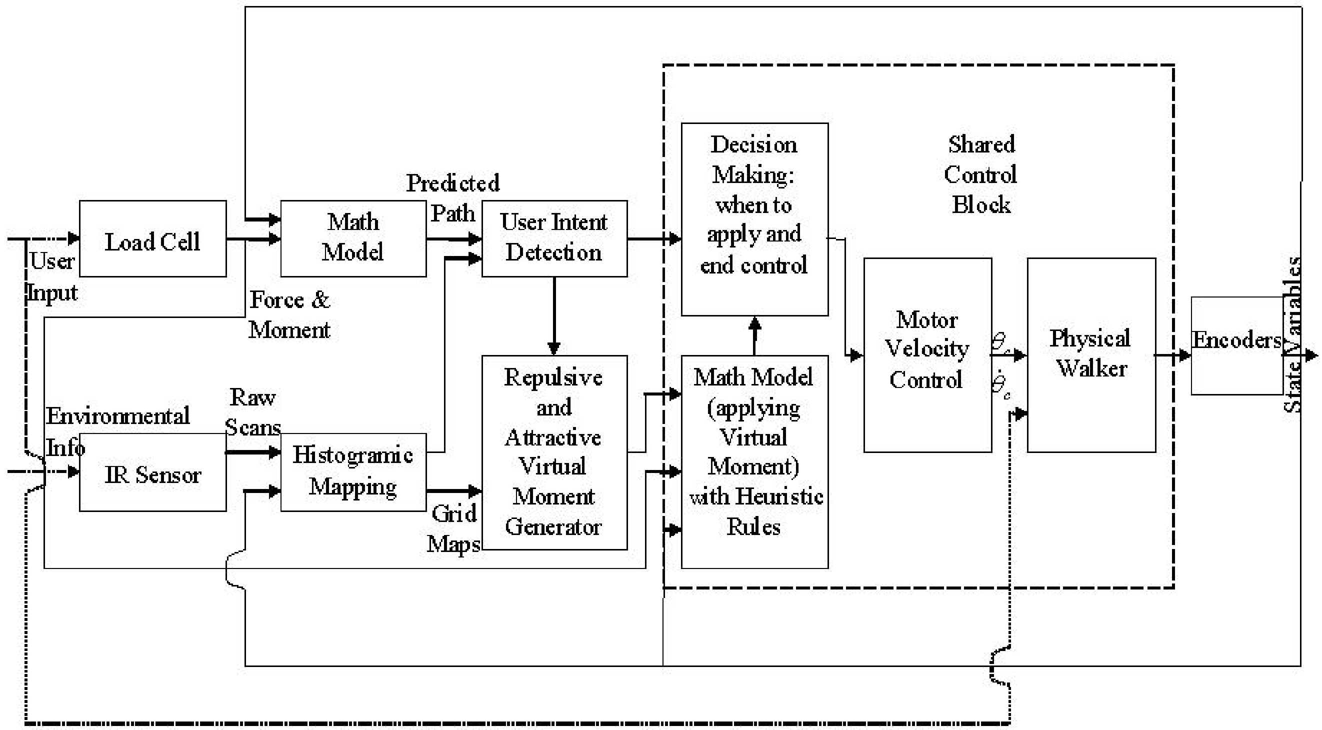

Figure 2. Shared control system architecture

Data Acquisition

The force-moment signals were sampled at 360 Hz using a laptop personal computer mounted on the walker and equipped with two PCMCIA data acquisition cards. The motion model (walker/user) was captured using reflective markers and the Vicon motion capture system 612 connected to six 120Hz video cameras (Vicon612 Technical Specifications). The Vicon system and the force moment data acquisition computer were synchronized using a synchronization channel between the two systems. The Vicon system creates a 3-D motion model by using the positions in the (x-y-z) space of particular real points (markers) placed on the human and the walker frame. In this model, seven markers represent the walker and thirty-eight were used for the human body.

A flat amplitude response IIR low-pass filter with a cut-off frequency of 3Hz is used in filtering the force-moment data. To eliminate the phase shift caused by filtering, a non-causal bi-directional filter was implemented. This filter performs zero-phase shift digital filtering by processing the force-moment data in both the forward and reverse directions (Signal Processing Toolbox User's Guide, The Mathworks Inc.).

Subjects

Experiments were conducted in the motion analysis lab on a total of twenty-two participants, fifteen of whom were older adults (above 65). Subjects had a mean age of 64.6±15.2 years (Min= 27, Max= 87 years), a mean height of 169.1±8.1 cm (Min= 158, Max= 183 cm), and a mean weight of 166.9±20.3 lb (Min= 131, Max= 210 lb). None of the subjects had any locomotor disability or used any assistive devices, including canes and walkers.

Experimental Procedures

Each user performed a total of 36 experiments emulating 11 navigational scenarios designed to assess the effect of control actions and conflict of intent, between the walker's computer control and the walker's user, on the stability of the user; a pre-experiment trial was aimed at calibrating the data capture systems, both with the users' hands on and off the walker. Each navigational scenario was performed 3 times. The following walker-assisted navigational scenarios were performed to evaluate the stability of the walker-user system:

1. Subject walked along a straight path with no intervention from the controller.
2. Subject made 30-degree turns (both right and left) with no intervention from the controller.
3. Subject made 60-degree turns (both right and left) with no intervention from the controller.
4. Subject made 30-degree turns (both right and left) with the controller aiding the turn (emulating obstacle avoidance, with agreement from the user).
5. Subject made 60-degree turns (right and left) with the controller aiding the turn.
6. Subject tried to stay on a straight line while the controller attempted to make a turn momentarily

(intent conflict between the controller and the user resulting in a "control fighting" scenario).

Of the above 5 cases, the first 3 represent the scenarios when the controller was passive and the navigation is completely controlled by the user. Scenarios described in 4 and 5 above examine the effect of the control actions on the walker-user system stability when the shared control assists the user in his/her navigation. Whereas scenarios described in 6 above are designed to evaluate the situations where the active controller of the walker may oppose the user-intended motion– like attempting to avoid an obstacle thinking the user is unaware of it, while the user is attempting to dock onto the obstacle.

Computation of Instantaneous Stability Margin

There are a number of methods to find the stability margin of a vehicle (Sugano, Huang, and Kato 1993), (Sreenivasan and Wilcox 1994), (Ghasempoor and Sepehri 1995); however, we applied the principle of force-angle stability, introduced in (Papadopoulos and Rey 1996), (Papadopoulos and Rey 2000), to measure the stability margin of the three-wheeled walker on-line due to its sensitivity to vertical weight distribution (heaviness of the top), and its sensitivity to angular loads including external forces and moments applied by the walker's user in our case. Although the method was designed for slow moving vehicles, force-angle stability measure computation can be fast due to its simplicity. Hence it is possible to measure the instantaneous stability margin of the walker on-line during navigation.

To measure the force-angle stability margin of the walker, the resultant force acting at the center of mass of the vehicle (f_r) should be computed, from forces and moments measured at the handles, along with the angle that the component of the resultant force about each tip-over axis (f_i) makes with the vector (l_i) normal to the corresponding tip-over axis. The model to compute the force-angle stability measure for the walker was implemented following the procedure outlined in (Papadopoulos and Rey 1996) and (Papadopoulos and Rey 2000). The walker's contact points with the ground form a triangular support base when projected on the horizontal plane. The three axes, each connecting two of the walker's three ground contact points, were taken as the candidate tip-over axis.

The resultant force on the walker's center of mass was calculated instantaneously by performing appropriate transformations on the measured external forces applied by the user and the gravitational load of the walker. It should be noted that the angular loads applied by the user should also be converted into an equivalent force couple for each tip-over axis. The Force-Angle stability measures associated with the i^{th} tip-over axis, as given in (Papadopoulos and Rey 1996), can be calculated as:

$$\alpha(i) = \theta(i)*F_r \qquad \text{(i)}$$

where θ(i) is the angle that the resultant force's component about the tip-over axis makes with the normal to that tip-over axis, and F_r is the resultant force. The overall force-angle stability measure of the vehicle is then calculated as the stability margin of the tip-over axis that has the minimum value of θ associated with it. Thus the global tip-over stability margin of the vehicle is given by

$$\alpha = \min[\theta(i)]*F_r \qquad \text{(ii)}$$

The magnitude of the stability margin indicates the degree of stability of the system. Higher positive values of α indicate a better stability condition of the walker. When the α value is zero, the vehicle is under critical stability and is about to tip over, whereas a tip over is in progress when the α values goes negative. Hence it is possible to exactly evaluate the degree of stability of the walker instantaneously during navigation. The continuous tracking of the stability margin also informs the controller of the trend of the stability for a brief history of time. For example, the scenario where stability margin continuously decreases at a steep slope for the past 0.6 seconds would indicate the proximity of a probable tip-over.

Results

The variations of instantaneous stability of the walker for various scenarios of navigation were obtained by computing the force-angle stability margin using the stability computation model presented above. It should be noted that the difference in the initial and final values of stability margin was attributed to the difference in the initial and the final postures of the user (the experiments start with the users not touching the walker's handles, then followed by putting their hands on the handles, but without leaning on the walker, and end with the user leaning on the walker's handles). The stability margin signals were filtered at a frequency of 6 Hz using a bilinear filter.

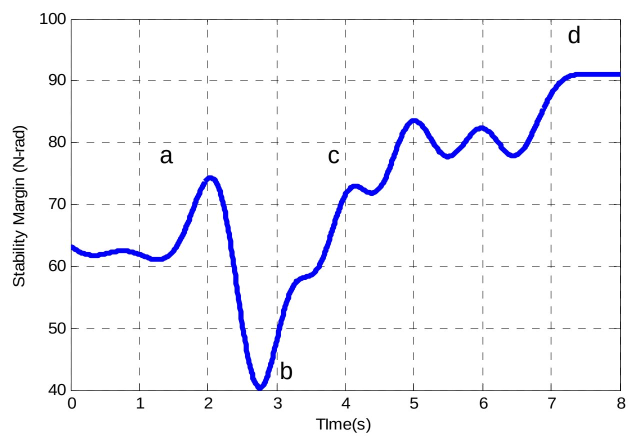

Figure 3. Force-angle stability margin variations for the "walking-straight" scenario

Figure 3 shows the variations of the stability margin of the walker as the user walked along a straight path. The period between ‘a’ and ‘b’ in the plot represents the decrease in the stability due to the acceleration of the walker under the initial propulsive forces applied on the handle by the user, the inertia of the walker, and the moment caused by the friction of the walker’s wheels with the floor. The increase in the stability margin, between ‘b’ and ‘c’, is attributed to the decrease in acceleration as the walker picked up speed. The variations of the stability margin in the plot between points ‘c’and‘d’ reflect changes in the stability margin with the user’s gait-cycle. A more detailed discussion on the variations of stability of the walker-user system based on the gait characteristics of the user will be presented elsewhere and is beyond the scope of this paper.

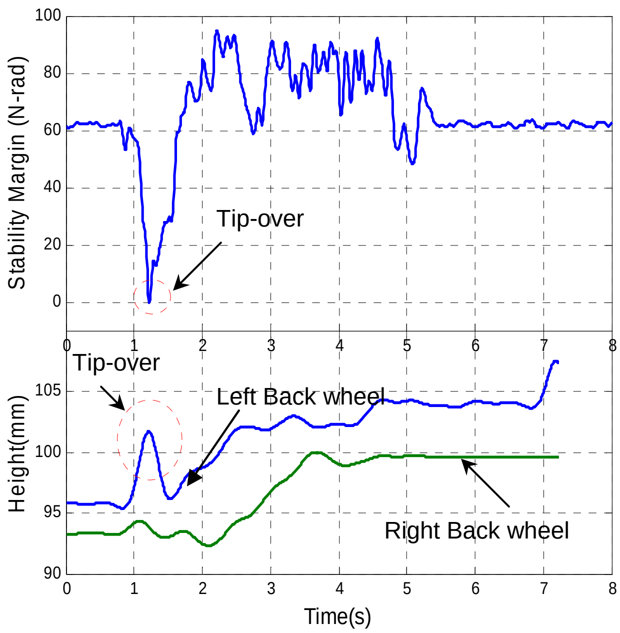

Figure 4. Near tip-over upon initial acceleration. The Lower graph shows the height of the left and right markers of the walker’s back wheels.

Figure 4 illustrates a near tip-over case when the subject propelled the walker with excessive force lifting on the left back wheel. The height of the markers on the back wheels clearly shows that the left back wheel lifted off the ground, and the lift-off instance corresponded with the near tip-over instance on the stability margin graph. In this graph, the stability margin signal has not been filtered to allow the accurate identification of the near tip-over instance. It is worthy to note that the consistent increase in height of the back wheels’ markers is due to a slight incline in the floor of the gait lab.

Figure 5 shows the variations of the stability margin when the user makes a 30 degree left turn. As observed from the plot, the stability of the system decreased during the turn (period between ‘a’ and ‘b’). The stability later increased once the user completed the turn and started to move along a straight path (period between ‘b’ and ‘d’). It is clear from the graph that the reduced stability region closely coincided with the time during which the turn was made, in comparison with the synchronized time trace of the displacement of the walker’s center of mass along the Y axis on the lower part of the graph.

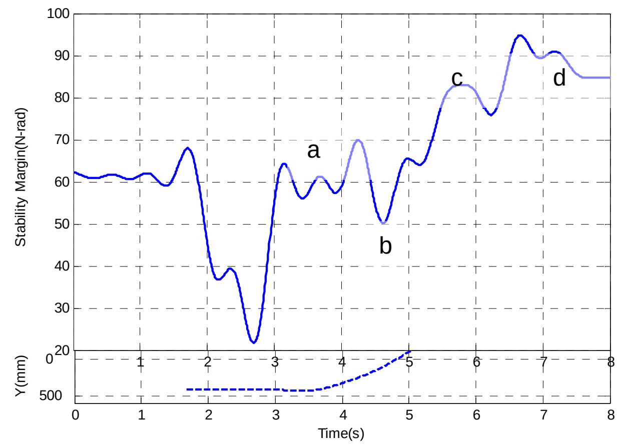

Figure 5. The trajectory of the walker and variations in the stability margin when a 30 degree turn was made.

The effect of making sharper turns on the stability of the walker is illustrated in Figure 6. In this case, the user made a 60-degree turn. As observed from the figure, there was a significant decrease in the stability margin of the walker as the user turned. A sharp decrease in the stability margin during the turn was incurred, indicated by the period between ‘a’ and ‘b’.

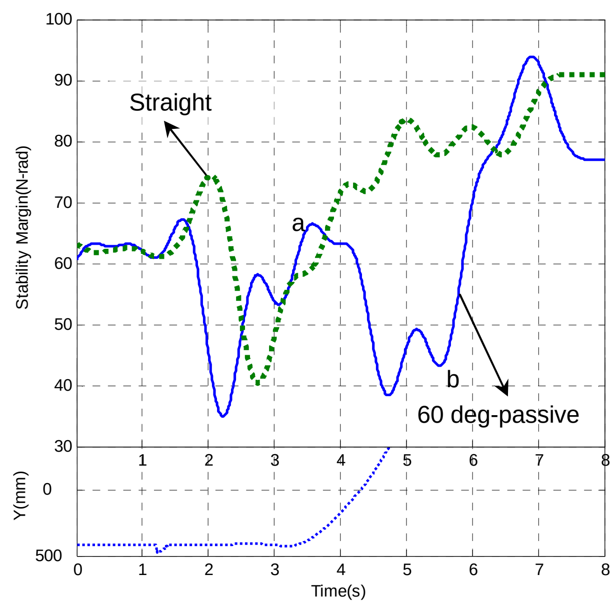

Figure 6. The trajectory of the walker and variations in the stability margin when the subject made a 60 degree turn.

A comparison of the decrease in the stability margin associated with different turns for the same user is depicted in figure 7. Clearly the reduction in the stability margin incurred while making sharper turns (60 degrees) was higher than while making a smoother turn (30 degrees). Additionally, the sharper the turn performed the longer the time needed to recover on the stability.

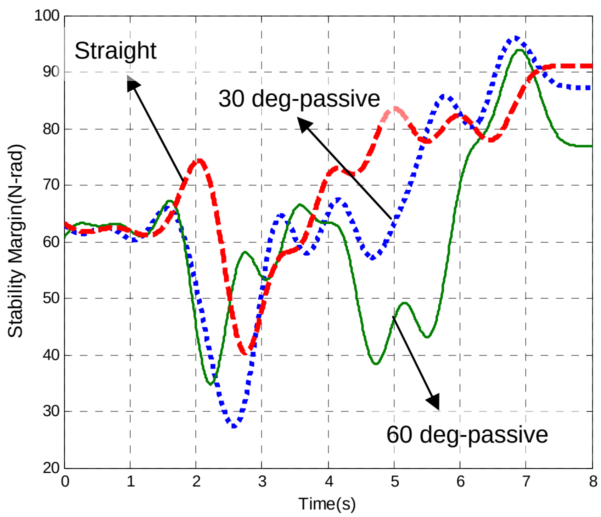

Figure 7. Comparison of stability profiles to show the effect of making sharper turns.

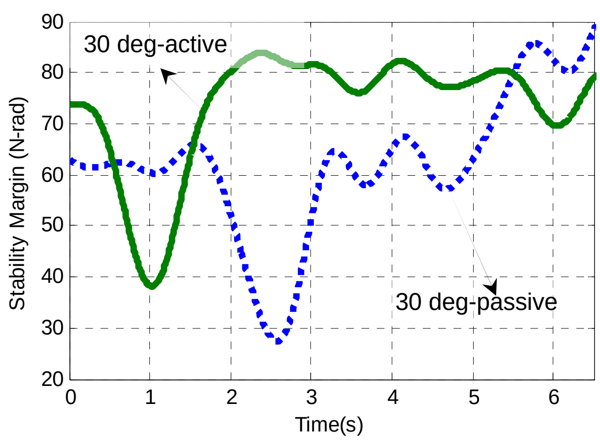

Figure 8. Comparison of stability profile when the controller was passive and when the controller aided the user in a 30 degree turn.

In Figures 8 and 9, we compare two scenarios of making turns for the same user – in the first the controller was inactive, and in the second the controller helped the user by steering the front wheel appropriately. This scenario was set up in the test environment by manually activating the controller to steer the front wheel at the appropriate time to aid the turn of the walker. As observed from the results, the stability of the walker was not reduced during the turn when the controller steered the front wheel as compared to the passive turn affected by the forces and moments applied by the walker's user.

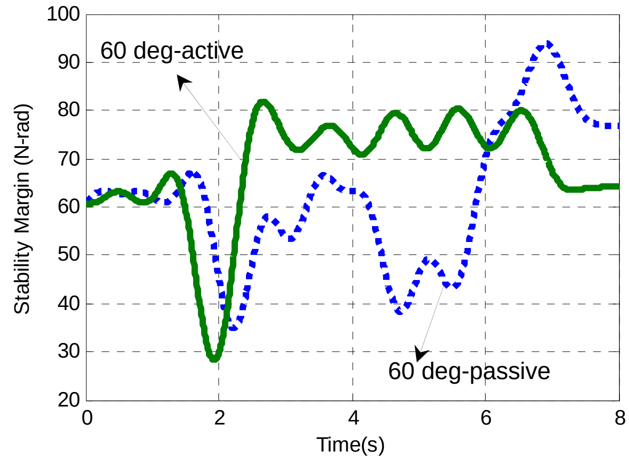

Figure 9. Comparison of stability profile when the controller is passive and when the controller aids the user in a 60 degree turn.

Figure 10 shows the stability variations when the controller attempted to steer the vehicle away from the user's intended direction. This scenario is expected to occur in a shared control system when the user's intent is wrongly identified by the walker, for example when the controller attempts to avoid an obstacle that the user is aware of and is trying to get close to (docking). From the plot, it is clear that the walker's stability margin was critically reduced (the period between 'c' and 'd' in Figure 10) during the period when the user tried to fight and override the walker's control action. This scenario emphasizes the need to monitor stability and to include stability as a decision criterion in future shared control algorithm designs to avoid jeopardizing the user's stability under any circumstances during navigation.

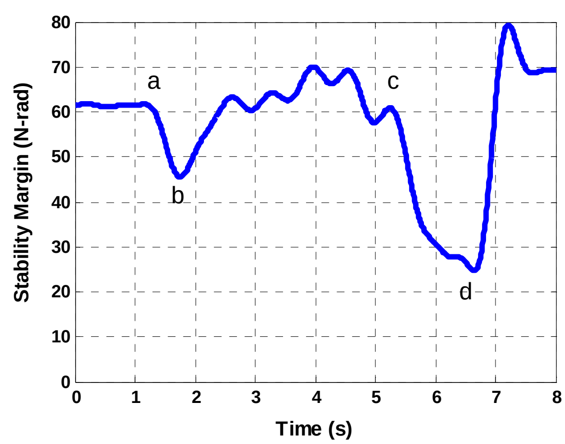

Figure 10. Near complete loss of stability during control fighting.

Discussion

The variations of the stability for different navigational scenarios performed by the same user quantitatively showed that assisted steering indeed enhanced the user's stability when the user's and the walker's intents were aligned. However, the results also indicated that a conflict between the user's intent and the walker's control actions (or walker's intent) in so called intelligent walkers could jeopardize the stability of the walker-user system, and hence that of the walker's user. These observations were fairly consistent across the subjects, but not all users caused the walker's back wheel to lift off upon starting to walk. The results call for intelligent walkers that continuously monitor the stability of the system to decide on the most appropriate time for the activation of the control to maintain/ enhance the walker-user system's stability especially when the controller is performing actions, such as obstacle avoidance, or is assisting the user pass through a narrow door-way. The knowledge of the instantaneous stability margin, as well as its history of the walker, may in turn enable the controller to predict potential near tip-over cases and hence may provide an opportunity to make/ change the controller's action to avoid tip-over of the system and a potential fall of the user. Such a controller will improve the safety of the users during the walker-assisted navigation and potentially give the users a more comfortable navigating experience. The above factors are very important, particularly, while designing intelligent walkers and similar navigational aids for the elderly, where maintaining the stability of the user is critical.

Conclusion & Future Directions

A stability computation model for a three-wheeled walker, based on the force-angle stability measure was presented. The variations in the stability for various walker-assisted navigation scenarios were shown and validated against motion capture data. The variation patterns of the stability calls for intelligent shared control architecture that decide on the course and timing of control actions based on the instantaneous as well as changes in stability margin of the walker-user system that may result from the execution of control action. A future research direction may also be designing mobility aids with adaptive structures that change their configuration in response to the user's stability needs. Additionally, the walker could be redesigned to provide feedback to the user to correct their walking style and encourage them to walk. Finally, further research is needed to investigate the stability of the complete human user/walker system and to infer the user's stability.

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