Application of Human Friendly Motion Control to Power Assist Wheelchair

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***Abstract* —Novel feedback control which is designed in human-friendly way is applied to power assist wheelchair. It provides this three-dimensional control of a wheelchair taking the operation situation into considerations; wheelchair needs controlling in the three dimensions: the longitudinal direction, the lateral direction, and the pitch direction. To this end, three assist controls are suggested: disturbance attenuation control is designed for the longitudinal and lateral directions and tip-over preventing control is designed for the pitch direction. These controls for three directions are combined appropriately. All these control designs are demonstrated and verified.**

***Keywords* — power assist wheelchair, three-dimensional control, impedance control, disturbance observer, tip-over prevention, operational state observer**

I. INTRODUCTION

Wheelchairs have been a great help for handicapped people. Nowadays power assist wheelchairs draw new attention as they are different from electric-power wheelchairs using joystick as an interface in the point that the riders should apply their torque to be assisted. They, however, adopt quite simple control algorithms; a feedforward control constituted by a gain to amplify the exerted propulsion torque and a low-pass filter to smooth the torque signal. Consequently they can not recognize external environments nor suppress unexpected external forces so that they cannot remove this gravity's effect and the user should provide all the force to hold his weight on the slope. This problem is addressed in Section II.

Tips and falls incidents of a wheelchair are another important problem. These incidents originate from exceeding the limits of the stabilities [1]. These stabilities of a wheelchair/rider system can easily be impaired by the gravity. However, assisting torque in power assist wheelchairs tends to cause tipping over on a slope, since the center of mass of the wheelchair is shifted near the axis of the rear wheels. This excessive torque should be addressed for safety of the user. We suggest an algorithm to determine this assisting torque in Section II.

The gravity also interferes with the heading direction of a wheelchair. On a side slope described in Figure 1, the wheelchair will easily turn by the gravity. It needs quite large force to keep going straight. In order to assist this force, the gravity's effect in the lateral direction also should be removed by a power assist controller. This assist control is designed in Section III

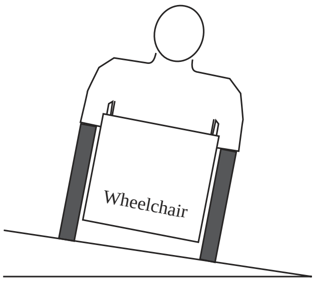


Fig.1. Gravity acting laterally on a wheelchair

Another point we should notice is the strategic difference in the design of gravity rejection control for each direction. The longitudinal disturbance should be rejected in the velocity level, and the lateral disturbance should be rejected in the position level. This difference can be implemented using the impedance concept; the relationship between the exerted disturbance torque and deviated values of position. Different types of feedback controllers will attain different impedances.

All information necessary for the proposed power assist controller is obtained by the operational states observer provided in the paper [3].

II. DESIGN OF DISTURBANCE ATTENUATION CONTROL IN THE LONGITUDINAL DIRECTION

A. Appropriated Impedance Design for Disturbance Attenuation in the Forward and Reverse Directions

Feedback control can adjust the impedance between the disturbance and the position or velocity of a wheelchair. In order to stop a wheelchair removing the gravity's effect on a hill, a wheelchair needs stiffness against the gravity that provides force in the opposite direction of the gravity. This is main idea which is adopted to produce appropriate torque to reject the gravity’s effect on a hill.

Original impedance of the wheelchair in the longitudinal direction can be depicted as $1/Js+B$ (Note that the impedance used in this paper is defined as a transfer function from the input torque to the output velocity). The torque to increase the inertia J and damping B in the impedance against the gravity is enough to decrease the velocity caused by the gravity.

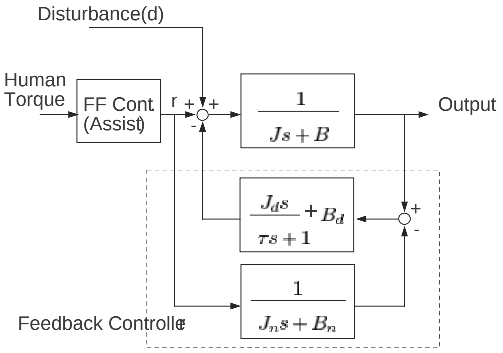


Fig.2. Structure of proposed disturbance attenuation controller for a wheelchair

Figure 2 is the proposed feedback controller. $1/Js+B$ is the dynamics of the wheelchair, and "FF Cont.(Assist)" means a feedforward controller to amplify the user's propelling torque measured by torsion sensors. This feedforward assist controller will be further discussed in the next section. Controller in the dotted rectangular is the feedback controller for disturbance attenuation. Assuming $J_n \cong J, B_n \cong B$, this feedback control changes the impedance as following:

$$\frac{1}{Js+B} \rightarrow \frac{1}{(J+J_d)s+(B+B_d)} \tag{1}$$

This increase in damping and inertia of a wheelchair makes the wheelchair react more heavily against the gravity. The amount of torque produced by the feedback controller can be modified arbitrarily based on J_d and B_d, and the frequency bandwidth of the torque also determined by B_d/J_d.

B. Combination with Tip-over Prevention Control

Tips and falls incidents tend to occur in the forward and backward directions [1]. Too large and radically changing assist torque in these directions can endanger the users. Taking this point into considerations, just to decrease the velocity of the wheelchair pulled down by the gravity is enough for the user, and this can be said to be more human-friendly. To this end, the assisting torque should be decreased during driving on a hill.

$$\frac{\alpha}{\tau s+1} \tag{2}$$

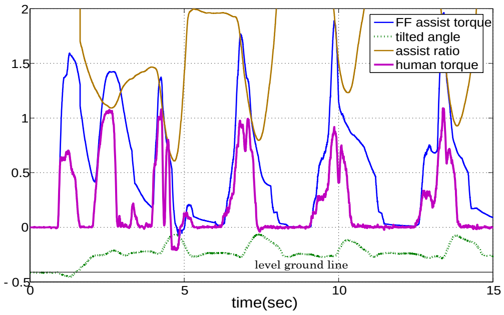
The filter in Equation (2) is adopted as the feedforward assist controller in Figure 2. For the tip-over problem, we have proposed a time-varying assist ratio control [2]. The assist ratio described as α is changed as follows;

$$\alpha = \alpha_{\max} \exp\left(\beta \frac{\dot{\varphi}_{CG}}{\varphi_{CG}}\right) \tag{3}$$

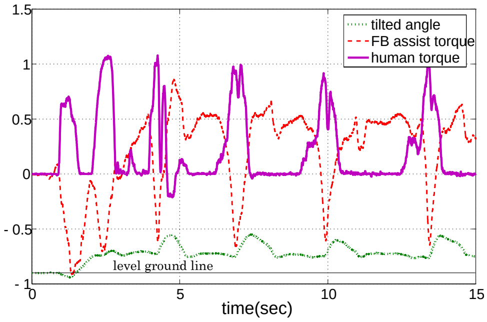
,where β is the time constant which decides the decreasing speed of the assist ratio α, and $\alpha_{\max}$ is the maximum assist ratio. φ_{CG} is the tilted angle of the center of gravity. This means the time-varying assist ratio decreases the assist torque according to the state of the wheelchair, which prevents the wheelchair from tipping over.

The assisting torque in proposed power assist control consists of feedforward portion and feedback portion: the feedforward torque for amplification of human torque with tipping over protection and the feedback torque for the gravity attenuation.

C. Experimental Results



(a) Decrease in feedforward assist torque by tip-over prevention control



(b) Independence between feedforward and feedback assist torque

Fig.3. Experiment of tip-over prevention control with disturbance attenuation control

Experiments to investigate the effectiveness of the combination of the proposed controllers are conducted. A power assist wheelchair climbed an incline with assistance of the proposed controllers. Figure 3 shows the results. In order to help understanding, the magnitudes of data are rescaled. Changes in data will be analyzed.

The dotted line means the tilted angle of the wheelchair chassis $\hat{\varphi}$ from the horizontal. This $\hat{\varphi}$ is changed by the condition of terrains on which a wheelchair traverses and also by tipping of the wheelchair which is described by some small peaks of $\hat{\varphi}$ in Figure 3.

The feedforward assist torque around these peaks of $\hat{\varphi}$ reveals the performance of tipping over prevention control. Soon after human torque is exerted, $\hat{\varphi}$ is about to rise. Then, the assist ratio decreases by the tip-over prevention control, leading to the decrease in the feedforward assist torque. During this period, the feedback controller offers negative torque due to the modeling error in $1/(J_n s + B_n)$. Figure 3 (b) shows the result of feedback disturbance attenuation control. While the rider does not propel the wheelchair, the feedback torque provides a constant value to compensate the gravity. These changes in feedforward assist torque and feedback assist torque verifies that the strategy we adopt is right; assisting torque satisfies two requirements for power assist control on sloping surfaces: prevention of tipping over and compensation of the gravity.

III. LATERAL DISTURBANCE REJECTION CONTROL

As is explained in the introduction, when a wheelchair crosses a side slope as described in Figure 1, it is difficult to manage the direction; because the gravity works as a disturbance that changes the direction. This section focuses on this problem.

A. Lateral Dynamics of a Wheelchair

First, the lateral disturbance that causes changes of the direction should be defined mathematically so that we can control it. Figure 4 shows the definition; the lateral disturbance is defined as the difference between the external disturbances on the left and right wheels. Disturbance, here, means the other external torque than the motor produces.

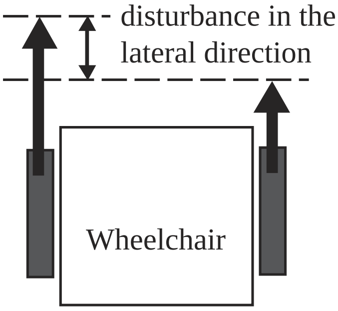


Fig.4. Definition of lateral disturbance

The control design for motion in the lateral direction needs different strategy from the control for the longitudinal direction. Human beings controlling a vehicle are accustomed to velocity control in the forward direction and position control to the lateral direction. This is made clear when we investigate to which kind of steady-state people are most sensitive.

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C. Design of Lateral Disturbance Rejection Control

The control design for motion in the lateral direction needs different strategy from the control for the longitudinal direction. Human beings controlling a vehicle are accustomed to velocity control in the forward direction and position control to the lateral direction. This is made clear when we investigate to which kind of steady-state people are most sensitive.

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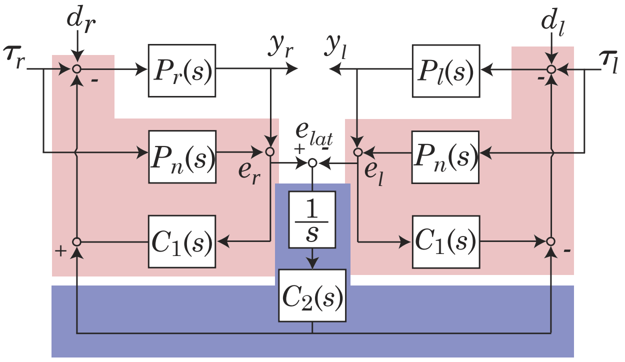

Fig.5. Structure of a lateral disturbance rejection controller - position control type

Small difference between the angles of two wheels makes a turn in the wheelchair. The lateral controller described in Figure 5 is designed to remove this difference, making high stiffness against the lateral disturbance force.

Note that the longitudinal disturbance attenuation controllers are included too. Controllers in the upper two colored area are the longitudinal disturbance attenuation controllers which has the same structure described in Figure 2. The controller in the below colored area is the lateral disturbance rejection controller. These two kinds of controllers constitute two dimensional disturbance suppression control of a wheelchair. A power assist wheelchair has two motors in both wheels so that it can achieve this two dimensional control.

In order to design $C_2(s)$ in Figure 5, the lateral disturbance is defined d_{lat} like Equation (4). d_r and d_l are the disturbance acting on the right wheel and the left wheel respectively.

$$d_{lat} = d_r - d_l \tag{4}$$

The purpose of this lateral direction control is to make the effect by this d_{lat} on $\int (e_r - e_l)dt$ as small as possible. To achieve position control, $C_2(s)$ should provide some stiffness against the lateral disturbances.

$$C_2(s) = \tfrac{1}{2}(K_D s + K_P) \tag{5}$$

Here, K_P works as the stiffness against the lateral disturbances which is a key parameter determining how much the controller suppress lateral disturbance. In spite of this existence of stiffness K_P, a constant lateral disturbance can cause a constant position error. If we want to reject that error, an integrator $\frac{K_I}{s}$ should be added in $C_2(s)$, but it may bring about some troublesome problems such as a wind-up to which integration is subject.

For suppression of the gravity in the longitudinal direction, $C_1(s)$ employs the controller described in Figure 2 and just increases the inertia and damping against the gravity. But the $C_2(s)$ allows us a strict disturbance rejection control in the lateral direction. This is the control strategy for the two dimensional disturbance suppression control of the wheelchair. In order to verify the effectiveness of the proposed control, two kinds of experiments are conducted: one is to see the disturbance rejection performance in the lateral direction, and the other is to see the independence between two controllers in the lateral and longitudinal directions.

C. Experimental Verification of Proposed Method

In order to verify the effectiveness of the proposed control, two kinds of experiments are conducted: one is to see the disturbance rejection performance in the lateral direction, and the other is to see the independence between two controllers in the lateral and longitudinal directions. In these experiments, the feedforward assist control in Figure 2 is not utilized in these experiments.

In order to measure external disturbances, we use torsion sensors to measure the torque exerted by the rider, which means we use human torques as disturbances. If feedforward assist control is not implemented, the applied human torque will not be assisted and just works as disturbances. These disturbance torques are used to see how our proposed controller works.

The performance of the lateral disturbance rejection control and independence between the longitudinal control and the lateral control are verified with an experiment. In this experiment, longitudinal disturbance attenuation control is not designed so strong. J_d and B_d in Figure2 is set small to decrease the performance of the longitudinal disturbance attenuation control.

In contrast, lateral disturbance control is designed strong enough to suppress the gravity's effect. This design will make distinction between performances of two controllers, and by this, the effectiveness of the lateral disturbance suppression control can be verified.

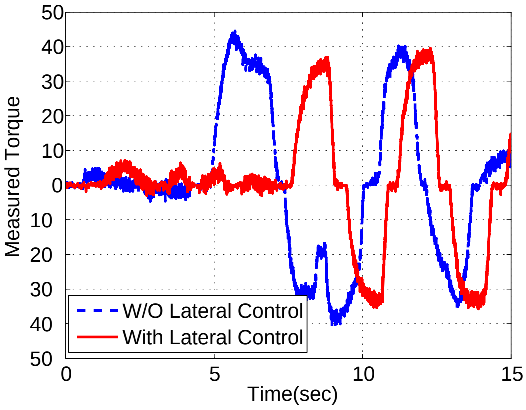

Fig.6. Disturbances in the same and opposite directions

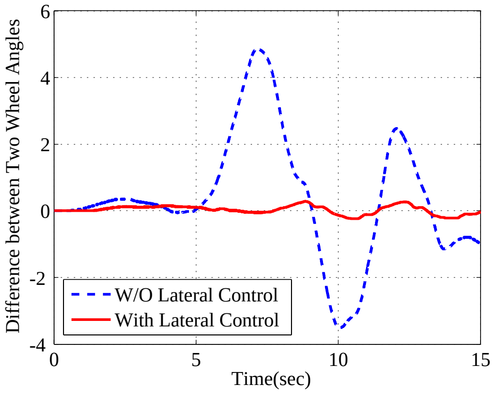

Fig.7. Independence of the control on the direction: wheel angles

Figure 6 and 7 illustrate that the proposed lateral control rejects only the lateral disturbance. Figure 6 is the measured disturbances, and it shows the disturbances on two wheels respectively. Until 7 second, both right and left disturbances are working in the same direction, which drives the wheelchair forward.

Angles described in Figure 7 shows that the wheelchair goes forward until 7 second and the disturbance is not removed. From 7 second, the torque works in the opposite direction. Although the magnitude of the torque is much larger, the angle driven by that torque is quite small. This represents that the proposed controller only rejects disturbances when they are applied in the lateral direction. This result ensures that the proposed controller that adopts two different strategies for two directions can be successfully implemented.

IV. CONCLUSION

We suggested three controllers for a power assist wheelchair and a method to combine those controllers and demonstrated enough safety and excellence in power assistance for a user.

REFERENCES

[1] Ronald P. Gaal, et al.: “Wheelchair Rider Injuries: Causes and consequences for wheelchair design and selection” *Journal of Rehabilitation Research and Development*, Vol.34, No.1, pp. 58-71, 1997.

[2] Naoki Hata, Yoichi Hori: “Backward Tumbling Control for Power Assisted Wheel-chair based on Phase Plane Analysis”, *Medicine and Biology*, 2003.9, Mexico

[3] Sehoon Oh, Naoki Hata, Yoichi Hori: “Control Developments for Wheelchairs in Slope Environments”, *American Control Conference*, pp.739-744, 2005.

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