Integrated Motion Control of a Wheelchair in the Longitudinal, Lateral and Pitch Directions

Sehoon Oh, Naoki Hata, Yoichi Hori
Institute of Industrial Science, University of Tokyo
Information & Electronics Division, Electrical Control System Engineering
4-6-1 Komaba, Meguro, Tokyo, 153-8505 Japan
{sehoon,hata}@horilab.iis.u-tokyo.ac.jp, hori@iis.u-tokyo.ac.jp

***Abstract*— The motion of a wheelchair is different from any other vehicles. It needs controlling in the three dimensions: the longitudinal direction, the lateral direction, and the pitch direction. This paper provides this three-dimensional control of a wheelchair taking user's manipulation into considerations.**

A power-assisted wheelchair is the main target of this paper. Three controls for all directions are combined to provide excellent assistance to a user. To this end, for the longitudinal and lateral directions, disturbance attenuation control is designed. For the pitch direction, tip-over protection control is designed. Lastly, we demonstrate all these controls can work independently for each purpose.

Key Words* : *power-assisted wheelchair, three-dimensional control, impedance control, disturbance observer, phase plane, disturbance observer

I. Introduction

A. Necessity of Three-dimensional Control for a Power-assist Wheelchair

Wheelchairs have been a great help for handicapped people. Nowadays power-assist wheelchairs draw new attention which can extend the advantage of those conventional wheelchairs. Although there are increasing demands for these power-assist wheelchairs, when it comes to the control of the power-assist wheelchairs, it cannot be said to be safe or easy to manipulate. They adopt quite simple algorithms; a feedforward control constituted by a gain to amplify applied manual torque and a low-pass filter to smooth the signal. Consequently they can not suppress unexpected external forces nor recognize external environments.

These safety problems easily appear on a slope. The conventional power-assist wheelchair cannot remove the gravity's effect so that the user should provide all the force to hold his weight on the slope; e.g. the conventional power assist control algorithms cannot support the user on the slopes. Moreover, excessive assist torque can cause tipping over on the slope. These are related to safety of the user and a novel control algorithm should be suggested to make the power-assisted wheelchair moves in a human-friendly way.

The gravity also interferes with the moving direction of a wheelchair. On a slope described in Figure 1, the wheelchair will easily turn by the gravity. It needs quite large force to keep going straight. Also, the force or torque necessary to keep the direction is much larger than the torque to go forward. This lateral disturbance also should be removed by a power assist controller.

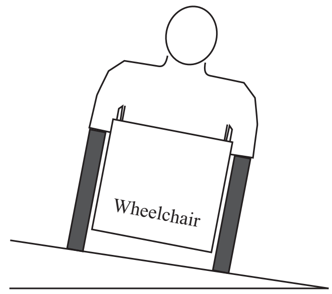


Fig. 1. Gravity acting laterally on a wheelchair

Another problem that can easily happen on a slope is tipping over of a wheelchair. Because the center of mass of the wheelchair is moved near the axis of the rear wheels on a slope, it can easily tip over and causes dangerous situation to its user.

B. Suggestion of Three-dimensional Power Assist Control for a Power-assisted Wheelchair

From these facts, we can see that the power assist controller for a wheelchair should achieve three-dimensional control: disturbance rejection for the longitudinal and the lateral directions and prevention of tipping over for the vertical direction. A controller that can satisfy all these requests will be designed in this paper.

Another point we should notice is that the difference in the design of disturbance-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 point will be reflected using the impedance concept; the relationship between the exerted disturbance torque and deviated values of position.

All information that is necessary for the proposed power assist controller is obtained by the states observer we provided in the paper [2].

II. Design of Disturbance Attenuation Control in the Longitudinal Direction

A. Appropriated Impedance Design for Disturbance Attenuation in the Forward Direction

A controller that attenuates the gravity's effect in the longitudinal or back and forward direction is developed in this section.

Feedback control can adjust the impedance between the disturbance and the position or velocity of a wheelchair. In order to stop a wheelchair on a hill removing the gravity's effect on the wheelchair, we need stiffness that provides the opposite direction force proportional to the deviated position. However, not so much large stiffness is necessary because it is not necessary to stop a wheelchair on a slope. Just to decrease the pulling velocity caused by the gravity is enough for the user, which can be said to be more human-friendly.

Original impedance of the wheelchair in the longitudinal direction can be depicted as $\frac{1}{Js+B}$. If the controller includes the stiffness, this impedance will be changed to $\frac{s}{Js^2+Bs+K}$ (K is the added stiffness by feedback control). However, this stiffness is not necessary as we discussed before, and it will be enough to increase the inertia J and damping B in the impedance just to decrease the pulling velocity.

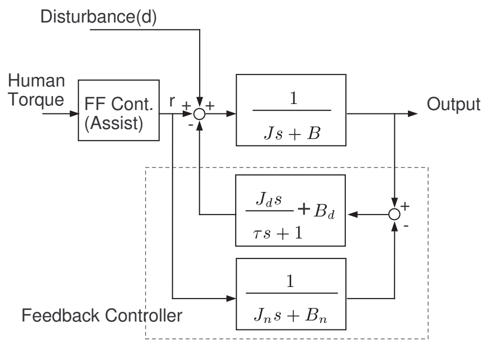


Fig. 2. Structure of proposed disturbance attenuation controller for a wheelchair

Figure 2 is the proposed feedback controller for the disturbance attenuation in the longitudinal direction. $\frac{1}{Js+B}$ is the dynamics of the wheelchair, and "FF Cont.(Assist)" means a feedforward controller to amplify the user's propelling torque. This feedforward assist controller will be $\frac{\alpha}{\tau_f+1}$, where α is an assist ratio. Further discussion on this feedforward assist control will be done in the next section. Controller in the dotted rectangular is the feedback controller for the disturbance attenuation. 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 the damping and inertia of a wheelchair makes the wheelchair seem heavier to the gravity. The amount of force produced by the feedback controller can be modified arbitrarily based on J_d and B_d.

B. Experimental Results

On this disturbance attenuation control for the longitudinal direction, an experimental result is analyzed in the paper [2]. In this paper, to assess the effect of the controller on downward

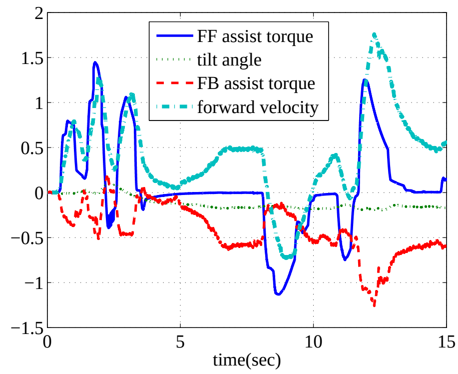


Fig. 3. Assist torque on a downhill

hill, another experiment is conducted on downward hill. Figure 3 describes the result.

Here, the tilt angle described as dotted line in the Figure 3 shows that from 4 second the wheelchair goes into a downhill. Then, the feedback assist torque described as the dashed line increases gradually and finally it reaches a certain value. During the period from 7 second to 8 second, the wheelchair moves on at a constant velocity and this is the reduced pulling velocity. This result is caused by the type of impedance that the feedback control adopts.

Around 12 second, the user applies his torque to move on to the forth, which means positive feedforward assist torque that may accelerating the pulling velocity and endanger the user is applied. However the negative feedback assist torque also increases and it leads to slow acceleration so that it can ensure the safety of the user.

During level road operation from 0 second to 3 second, and backward propulsion on the downhill from 8 second to 10 second, the feedback assist torque is generated in the opposite direction of the feedforward torque. This is due to the difference between the nominal dynamics $\frac{1}{J_ns+B_n}$ in Figure 2 and the real dynamics of the wheelchair. The proposed controller produces the feedback torque according to the difference between simulated velocity and the actual velocity; that is, not only external force but also modeling error will cause the feedback assist torque. If the nominal parameters J_n and B_n are set bigger than the real values and the simulated velocity is smaller than the actual velocity, negative feedback torque is produced to track the actual velocity to the simulated velocity. This is the reason why the opposite torque to the feedforward torque is produced by the proposed feedback controller in the above experiment. Nevertheless, due to the impedance configuration in the feedback controller is not so stiff that this opposite feedback torque is not so large.

III. Combination with Tip-over Protection Control

A. Tip-over Protection Control

In last section, a power assistance that compensates the gravity on a hill is proposed. However, there is another problem when we control a wheelchair on a hill. The wheelchair will be tilted and its center of balance will shift to the unstable area, on a hill, that is, inadequate power assistance makes the wheelchair unstable and tip over, because assisting power will work in the same direction with gravity.

To cope with this problem, we start with the composition of assisting torque. Now that we employed the feedback controller in last section, the assisting torque consists of feedforward portion and feedback portion. Between these portions, the feedforward portion accounts for tip over of the wheelchair, because its magnitude and momentum is much larger than those of feedback portion.

The feedforward portion amplifies the torque applied by the rider. It consists of a first-order time delay given as

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

where α is power-assist ratio and τ is the time constant of first order delay. τ is set smaller at the beginning of propelling and larger at the ending:

$$\tau=\begin{cases}\tau_{fast} & \frac{d}{dt}T_{human}>0\\ \tau_{slow} & \frac{d}{dt}T_{human}<0\end{cases}, \quad (\tau_{fast}<\tau_{slow}) \tag{3}$$

Following values are adopted as τ.

$$\tau_{fast}=0.08[s], \quad \tau_{slow}=1.0[s]. \tag{4}$$

For the tip-over problem, we propose assist control which has a varying assist function[1]. The assist ratio described as α is changed as follows:

$$\alpha=\alpha_{\max}\exp\left(\beta\frac{\dot{\varphi}_{CG}}{\hat{\varphi}_{CG}}\right), \tag{5}$$

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.

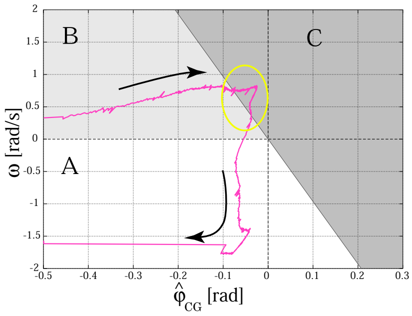


Fig. 4. Tip-over protection control using phase plane of $\hat{\varphi}$

Figure 4 shows the phase plane of $\hat{\varphi}$, which divides the plane into three regions depending on the level of danger: A) proper safety zone ($\omega_p<0$ and below the negative slope asymptote), B) semi-safety zone ($\theta_p<0, \quad \omega_p>0$ and below the negative slope asymptote), and C) dangerous zone (above the negative slope asymptote). During stable operation, the state of a wheelchair generally stays in the safety zone A. But it will shift to C region through B region when the wheelchair tips over by excessive torque. The trajectory in Figure 4 shows the result of stabilizing control which decreases the torque to remove the momentum of pitching movement. The time-varying $\alpha(t)$ achieves this decrease in torque according to the state of the wheelchair.

This φ_{CG} can be correctly observed using the state observer we proposed in [2]. In this research, the variable assist ratio α is decided using $\hat{\varphi}$ estimated by the operation state observer and the angular velocity φ of the chassis measured by a gyroscope. Equation (6) shows this strategy. $\hat{\varphi}_0$ is the constant angle between the center of gravity and the wheelchair chassis.

$$\alpha=\alpha_{\max}\exp\left(\beta\frac{\dot{\varphi}}{\hat{\varphi}-\hat{\varphi}_0}\right), \tag{6}$$

Another noticeable point is the independence of this tip-over protection control from the forward-direction-disturbance attenuation control. The control to prevent a wheelchair from tipping over is a feedforward control. On the other hand, the control that attenuates the gravity's effect on the wheelchair is a feedback control. These two controls work independently (See Figure 2).

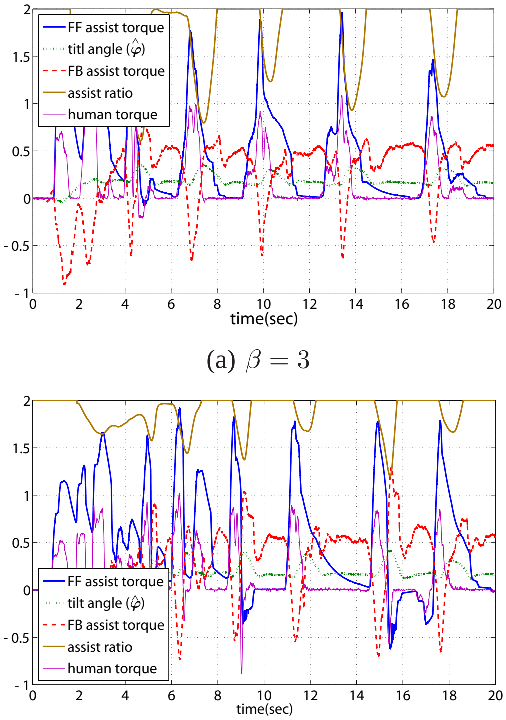
Moreover, from the viewpoint of the frequency domain, they are also independent. The tip-over protection control changes the ratio α especially when the rider starts to propel. This means $\frac{d}{dt}T_{\text{human}}>0$ and the time delay of feedforward assisting control τ_{fast} is small according to the equation (3). In this meaning, the feedforward tip-over protection control is related to the high frequency region. The gravity-attenuation control feedbacks the velocity information, and it has a certain amount of time delay which is roughly equal to the time delay of the wheelchair dynamics itself, $\frac{J}{B}$. This is large enough compared with τ_{fast}, and consequently the gravity-attenuation control is mainly related to the low frequency region. These points are studied later using the experimental results.

B. *Experimental Results*

Experiments to assess the combination of the proposed feedback controller with the tip-over protection control are conducted. To investigate the effect of the tip-over protection controller on the proposed feedback control, two experiments are conducted changing the β in Equation (6). Figure 5 shows the results.

At first, let us note the dotted line which means the tilt angle of the wheelchair chassis. This is estimated angle of φ in Figure 5 which indicates the inclination angle of the wheelchair chassis. The φ is changed by the condition of terrains on which a wheelchair traverses and also by wheelie, or lift of the front wheels. In all experiments, as the wheelchair goes up to a hill, the estimated $\hat{\varphi}$s increase and arrive at a certain constant value representing the angle of the hill. On the hill, the pilot exerts some torque to the wheels and it causes the lifting of front wheels, which is described by a peaks of $\hat{\varphi}$ in Figure 5.

We need to scrutinize the values of the feedback assist torque and the feedforward assist torque around these peaks of



(a) $\beta = 3$

(b) $\beta = 1$

Fig. 5. Experiment of tip-over protection control with disturbance attenuation control

$\hat{\varphi}$ to reveal the performance of the combination. Let us take a close look around those peaks in the upper figure. First, human torque is exerted, and when $\hat{\varphi}$ is about to rise, the assist ratio decreases leading to the decrease in the feedforward assist torque. During this period, the feedback controller offers negative torque due to the modeling error in $\frac{1}{J_n s + B_n}$. After the decrease in the feedforward torque, the feedback torque returns to the constant value to compensate the gravity force. Figure 5 (b) is the result of the experiment with $\beta = 1$. With this control parameter, the decrease in the feedforward is insufficient, and consequently the peak of $\hat{\varphi}$ is higher than that of (a), which means the protection of tip is insufficient and results in tipping over. As discussed before, since the feedback controller provides a certain amount of torque to compensate the gravityfs force, β in the tip-over protection control should be smaller than that of without the feedback control.

This behavior of assist torque satisfies two requirements for power assist control on sloping surfaces: prevention of tipping over and compensation of the gravity. Figure 6 depicts the same experimental result with Figure 5 (a) but with the combined torque of the feedback and feedforward control.

One noteworthy point is the behavior of this combined torque after the feedforward torque is reduced by the decrease in the assist ratio. During some period after the decrease, the combined torque tends to keep a larger value than the value of the feedback torque provided while there is no human input. This additional torque is due to the feedback assist torque (see

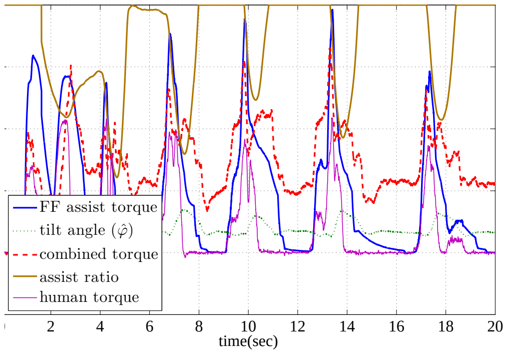


Fig. 6. Integrated assist torque during wheelies

the same part of Figure 5) and helps reducing the dropping speed of the front wheels. This prevention of rapid shift in the center of gravity is another feature of the proposed disturbance attenuation control.

IV. Lateral Disturbance Rejection Control

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

A. Lateral Dynamics of a Wheelchair

First, the lateral disturbance that causes changes of the moving direction should be defined mathematically so that we can control it. Figure 7 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.

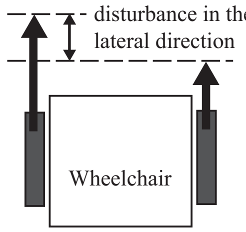


Fig. 7. Definition of lateral disturbance

This definition of lateral disturbance may seem too simple to explain the lateral motion in detail. The lateral dynamics of a four-wheel vehicle such as a car is, in general, described in a more complicated way. However, the lateral dynamics of a wheelchair is simpler than that of a car. The front wheels of a wheelchair are casters and not restricted. Thus, the front wheels produce neglectable amount of cornering forces. This justifies the definition of lateral disturbance in Figure 7.

B. Important Feature in the Lateral Control of a Wheelchair

For human-friendly motion control, the lateral direction needs different strategy from the disturbance suppression control for the forward direction. Human beings in 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.

This is the point we should take into consideration when we design lateral control for a wheelchair. Based on this idea, two controllers will be suggested

C. Two Types of Lateral Disturbance Rejection Control

Figure 8 is the proposed controllers for disturbance rejection in the lateral direction.

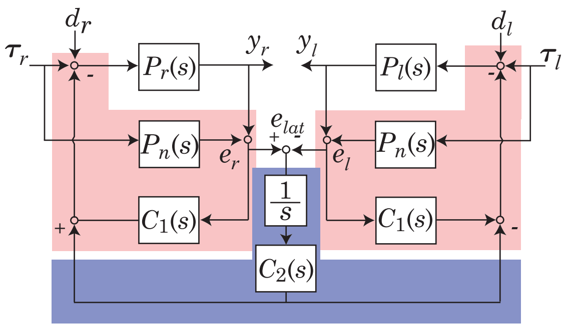


Fig. 8. Structure of a lateral disturbance rejection controller - position control type

As discussed in the last section, small difference between the angles of two wheels makes a turn in the wheelchair. The lateral controller described in Figure 8 is designed to remove this difference. This controller can make high stiffness against the lateral disturbance force.

What is noticeable is that in this Figure, the forward disturbance attenuation controllers are included too. Controllers in the red colored rectangles are the forward disturbance attenuation controllers, and the controller in the blue colored rectangle is the lateral disturbance rejection controller. These two kinds of controllers constitute two dimensional disturbance suppression control of a wheelchair. A power assistive 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 8, the lateral disturbance be defined d_{lat} like equation (7). d_r and d_l is the disturbance acting on the right wheel and the left wheel respectively.

$$d_{lat} = d_r - d_l \tag{7}$$

The purpose of this lateral assistance control is to make the effect by this d_{lat} on $e_r - e_l$ as small as possible. Let's define this $e_r - e_l$ as e_{lat}. Considering the transfer function from d_{lat} to e_{lat}, the controller $C_2(s)$ can be designed.

The transfer function in Figure 8 is

$$T_{lat2}(s) = \frac{e_r - e_l}{d_{lat}} = \frac{P}{1 + P(C_1 + 2\frac{C_2}{s})} \tag{8}$$

To achieve position type control, $C_2(s)$ should provide some stiffness against the lateral disturbances.

$$C_2(s) = \frac{1}{2}\left(K_D s + K_P\right) \tag{9}$$

This $C_2(s)$ makes the transfer function

$$T_{lat2}(s) = \frac{1}{(J + J_d)s^2 + (B + B_d + K_D)s + K_P}. \tag{10}$$

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 e_{lat}. 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 wind-up to which the integration is subject.

A disturbance observer can be adopted for this lateral control, and [3], [4] have suggested that disturbance observer as a lateral disturbance rejection controller for a wheelchair. However, the disturbance observer has an inverse dynamics of a wheelchair and is quite sensitive to unknown dynamics. To achieve robust performance, the provided position-control-type disturbance attenuation control may be preferred.

For suppression of the forward gravity, $C_1(s)$ employs the controller described in Figure 2 and just increases the inertia and damping against the forward 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 attenuation control of the wheelchair.

D. Experimental Verification of Proposed Method

For the lateral disturbance rejection control verification, the following two points are considered in the experiment:

- Forward disturbance rejection control is not designed so strong, which means J_d and B_d in Figure 2 is small.

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

- Torque exerted by the user is not assisted so that the torque will work as disturbance.

This means that we use human torques as lateral disturbances. Those disturbance torques can be measured and help us see how our proposed controller works. Figures 9 to 11 are the results. The lateral controller of the force type in Figure 8 is experimented.

Figure 9 shows the exerted torques as disturbance, and this disturbance is calculated by subtracting two exerted human input torques. The blue dotted torque is applied to a wheelchair without the lateral control, and the red line is to a wheelchair with the lateral control. At the beginning (to 5 second in the w/o control case, and to 7 second in the with control case), the right and left torques are exerted in the same direction so that the lateral disturbance, or the difference between the left and

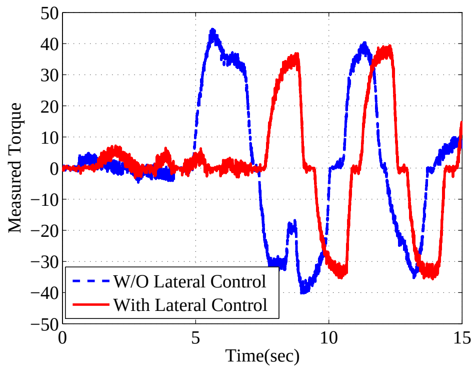


Fig. 9. Exerted lateral disturbances

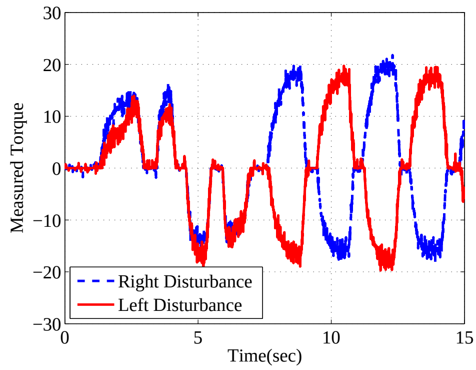


Fig. 11. Disturbances in the same and opposite directions

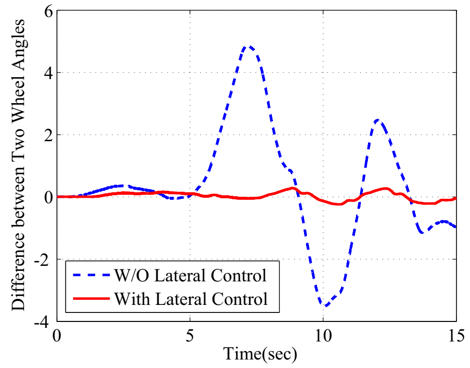


Fig. 10. Differences between the right and left wheel angles

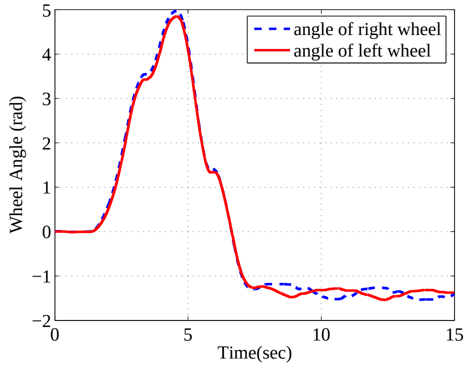


Fig. 12. Independence of the control on the direction: wheel angles

the right input torque is not so large. After that period, the torque is applied in the opposite directions, and it produces quite large lateral disturbance.

Figure 10 is the output of this applied torque, and shows the differences between the right and left wheel angles. Without the lateral control, the difference becomes large, and this will make the wheelchair turn against the user's will. While, with the control the difference does not become so large that the lateral disturbance does not interfere with the moving direction.

Independence between the forward control and the lateral control is also verified with experiments. In the following experiment, J_d and B_d in Figure 2 are designed smaller to decrease the performance of the forward disturbance attenuation control.

Figure 11, 12 shows that the proposed lateral control rejects only the lateral disturbance. Figure 11 is the measured disturbance, 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 straight. Angles described in Figure 12 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 and the right and left disturbances are eliminated. This makes clear that the proposed controller rejects disturbances when they are applied in the opposite direction, which means that proposed controller rejects only the lateral disturbance.

V. Conclusion

We suggested three controllers for a power-assisted wheelchair and a method to combine those controllers. Control for the longitudinal direction and lateral direction are designed in terms of human-friendliness and they can function as desired respectively, for two motors are utilized in a power-assisted wheelchair. For the longitudinal direction, two proposed controllers can cooperate with each other as they work in different frequency bandwidth. By experiments, we demonstrated enough safety and excellence in power assistance for a user.

References

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

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

[3] Seiichiro Katsura, Kouhei Ohnishi: "Advanced Motion Control for Wheelchair Based on Environment Quarrier", *Trans. IEE of Japan*, Vol. 125-D, No. 7, pp. 698-704, 2005.

[4] Takeaki Sugimoto, Hirokazu Seki, Susumu Tadakuma: "Rectilinear Driving Improvement of Power Assisted Wheelchair Based on Disturbance Estimation of Right and Left Wheels", *Japan Industry Applications Society Conference 2004*, Y-35, 2004.