Lateral Disturbance Rejection and One Hand Propulsion Control of a Power Assisting Wheelchair

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Abstract— **Many controls of a power assisting wheelchair have been proposed for the forward direction. But, there are not so many researches on the lateral control designs. This paper copes with two problems that can easily happen in wheelchair driving: keeping the wheelchair straight despite disturbances in the lateral direction and driving with only one hand. Lateral disturbance rejection control design should be different from the forward disturbance attenuation control. Our control design takes this point into account, so it can offer excellent lateral support. This lateral control is also related with one hand propulsion of the wheelchair. Changing the extent of controls can achieve the one hand propulsion. That extent will be decided based on the user's intention, and that intention can be estimated using a phase plane. These control designs are experimented.**

Key Words : ***power assisting wheelchair, lateral control, lateral disturbance, disturbance observer, gravity rejection, phase plane, one hand propulsion***

I. Introduction

A. Necessary Assistance in the Lateral Direction

Power assisting wheelchair is a good application of welfare control. Motors assist human power but it should not be so much that the user does not feel awkward. Further more it should provide enough power which will satisfy the user. Power assist in moderation is not so easy, which makes the control design difficult.

Fig. 1. Commercial Power Assisting Wheelchair

Recently, various controls for this wheelchair are researched. However, many of those researches are on the forward control. When the ground on which a wheelchair is running is inclined laterally like figure 2, the wheelchair cannot go straight by the gravity acting laterally on it. To keep the wheelchair straight can be so big a burden to the user that some assistance in this direction is necessary. Nevertheless this kind of assistance control is not researched so much. This paper copes with this problem.

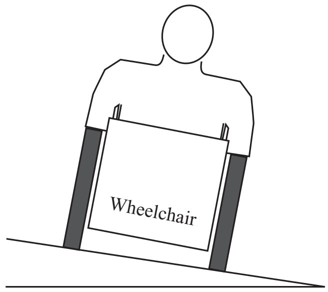

Fig. 2. Gravity Acting Laterally on a Wheelchair

The other controller this paper provides is one hand operation of a wheelchair. There are some cases where one drives a wheelchair with one arm disabled. One hand operation control enables this driving. For the control, the user's intention whether he wants to go straight or turn should be sensed by the controller. We will use the phase plane of the torque exerted by the user.

B. Outline of This Paper

1. Keeping the wheelchair straight against lateral disturbances
2. One hand propulsion

These two are main topics in this paper. Section II and III will handle two topics respectively. In section II, we will consider the gravity's effect in the forward and lateral directions. Two types of controller will be proposed to attenuate each effect. In section III, the characteristics of human torque to a wheelchair is analyzed firstly, then based on that characteristics a controller that allows the user to move his wheelchair with one arm is proposed.

II. Lateral Disturbance Rejection Control

A. Problems Caused by the Gravity

Propulsion of a wheelchair on a slope is heavier burden than on level ground. Figure 3 compares necessary torques for propulsions in these two cases. It shows that necessary propulsion torque on hills is much larger than the torque for level ground propulsion. This means the power assistance control is more necessary on hills. In this point, the assistance is not only multiplying the exerted human power, but it also should provide the compensational power to attenuate the gravity's effect. This assistance should work in two different ways: the forward assistance and the lateral assistance.

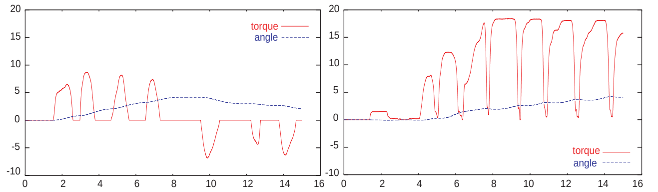

Fig. 3. Necessary Torques to Drive a Wheelchair (Upper: drive on level ground, Lower: drive on hill)

Assistance against the forward gravity can be done by velocity control, but for the lateral gravity, position control is necessary. This will be explained in the next section.

B. Control Designs for the Disturbance Rejection

Figure 4 shows the structure of proposed the forward disturbance attenuation controller. The two-degree-of-freedom controller is applied.

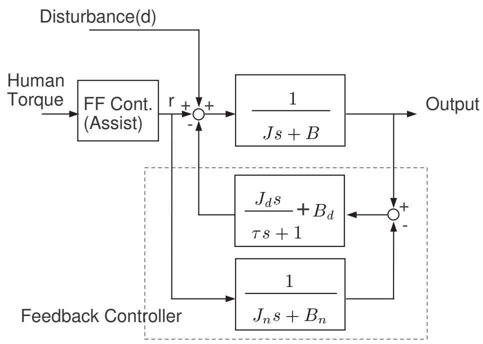

Fig. 4. Structure of Forward Disturbance Attenuation Controller

$\frac{1}{Js+B}$ is the dynamics of the wheelchair, and "FF Cont.(Assist)" means a feedforward controller for a power assistance, which measures the human torque and amplifies it by several times with a low pass filtering. Controller in the dotted rectangular is the forward gravity compensation controller.

This feedback controller aims to increasing the friction and inertia of the wheelchair against the gravity, which makes the wheelchair seem heavy to gravity. Equation (1) shows the change in the inertia and damping by this feedback. This can be a kind of the compliance control[1].

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

This control feedbacks the velocity, which means it is a kind of velocity control. Assistance for the forward gravity does not require the wheelchair to stop on a slope, and just decreasing the velocity by the gravity is enough. The wheelchair runs at very slow speed and it also stops frequently. The measurement of the velocity to feedback is done using the kalman filter we have proposed [4].

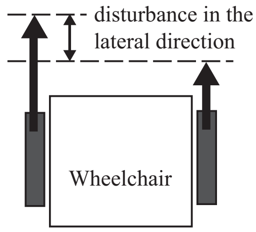

Fig. 5. Definition of Lateral Disturbance

On the other hand, The lateral disturbances such as the lateral gravity can be defined as the difference between the external forces on the left and right wheel(see the figure 5). Based on this idea, two controller are suggested in figure 6 and 7.

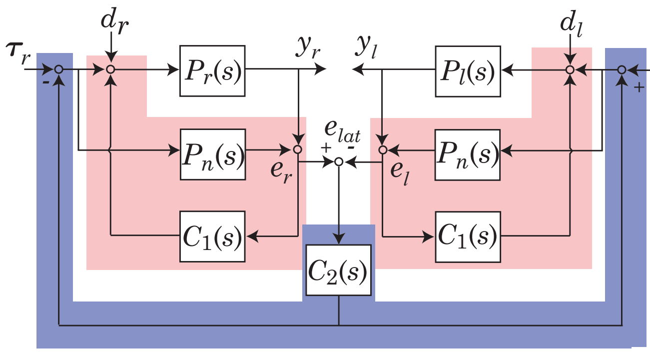

Fig. 6. Structure of Lateral Disturbance Rejection Controller - Force Control Type

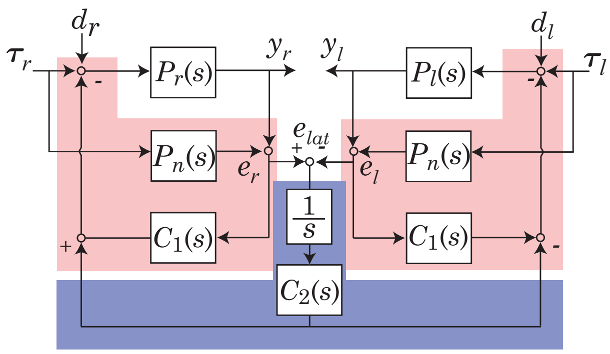

Fig. 7. Structure of Lateral Disturbance Rejection Controller - Position Control Type

At first, note that some offset in position caused by the gravity is not a big problem in the forward direction, but it is not in the lateral direction. Small difference between the angles of two wheels makes a turn in the wheelchair. This makes the lateral control design different from the forward one.

We suggest two types of lateral controls. One is force type that removes the lateral disturbance force; the other is the position type which makes high stiffness against the lateral disturbance force. Figure 6 is the force type control, and figure 7 is the position type control. In these figures, the forward disturbance attenuation controllers are included too. Controllers in the red colored rectangles are the forward disturbance attenuation controllers, and controllers in the blue colored rectangles are the lateral disturbance rejection controllers.

Let the lateral disturbance be defined d_{lat} like equation (2). d_r and d_l is the disturbance acting on the right wheel and the left wheel respectively.

$$d_{lat} = d_r - d_l \tag{2}$$

The purpose of this lateral assistance control is 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 the figure 6 is

$$T_{lat1}(s) = \frac{e_r - e_l}{d_{lat}} = \frac{P}{1 + PC_1} - \frac{2PC_2P}{1 + PC_1}, \tag{3}$$

where $P_r = P_l = P_n$ is assumed.

To make this transfer function insensitive $C_2(s)$ is designed like equation (4).

$$C_2(s) = \frac{1}{2}\frac{P_n(s)}{\tau s + 1} \tag{4}$$

This makes the transfer function $T_{lat1}(s)$ 0 ideally.

It is interesting that this $C_2(s)$ works as a disturbance observer in the lateral control [2], [3]. $C_1(s)$ employs the controller described in the figure 4 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 our control strategy in the two dimensional disturbance attenuation control of the wheelchair.

The transfer function is different in the figure 7.

$$T_{lat2}(s) = \frac{e_r - e_l}{d_{lat}} = \frac{P}{1 + P(C_1 + 2\frac{C_2}{s})} \tag{5}$$

For this position type control, $C_2(s)$ like below can provide some stiffness against the lateral disturbances.

$$C_2(s) = \frac{1}{2}(K_D s + K_P) \tag{6}$$

This $C_2(s)$ makes the transfer function

$$T_{lat2}(s) = \frac{1}{(J + J_d)s^2 + (B + B_d + K_D)s + K_P}. \tag{7}$$

Here, K_I works as the stiffness against the lateral disturbances. Though, a constant lateral disturbance can cause a constant e_{lat} error. If we want to reject that error, an integrator $\frac{K_I}{s}$ can be added in $C_2(s)$, but it may bring about some troublesome problems such as wind-up to which the integration is subject.

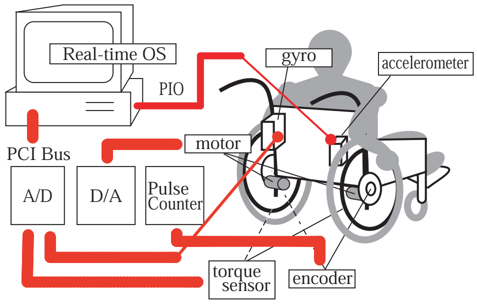

Fig. 8. Modified Assisting Wheelchair

C. *Experimental verification of proposed method*

The effectiveness of this gravity compensation controller are verified by experiments using the same experimental setup in figure 8.

Figure 8 shows the experimental setup. Two kinds experiment were done. One is done on level ground and the other is done on a hill. The result is shown in figure 9. In contrast to the drive on level ground, on a hill the controller produces a certain amount of motor torque while there is no human torque input. Almost same torque is produced even when the wheelchair descend the hill.

The amount of produced torque can be adjusted by the B_d parameter, and the parameter J_d will adjust the response time against gravity.

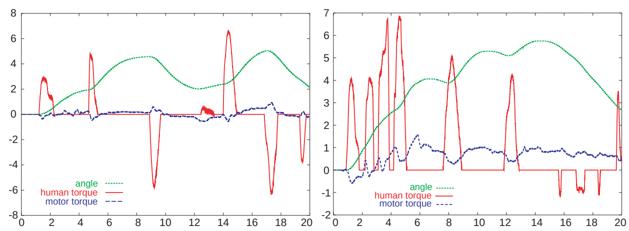

Fig. 9. Experimental Results (Left: drive on level ground, Right: drive on hill))

We should notice that this controller does not remove the effect of gravity perfectly, which means that this feedback controller will not stop the wheelchair on a hill. This is the point of proposed flexible disturbance rejection.

For the lateral disturbance rejection control verification, the experiment was done in this way:

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

This means that we use the human torques as lateral disturbances, and can measure those torques and see how our proposed controller works. Figure 10 to 12 are the results. The lateral controller of the force type is experimented.

Figure 10 shows the exerted torques as disturbance. The blue dotted line was done without the lateral control, and the red line with the lateral control. For the first 5 to 7 seconds, the right and left torques are exerted in the same direction so that the differences are not so large. But

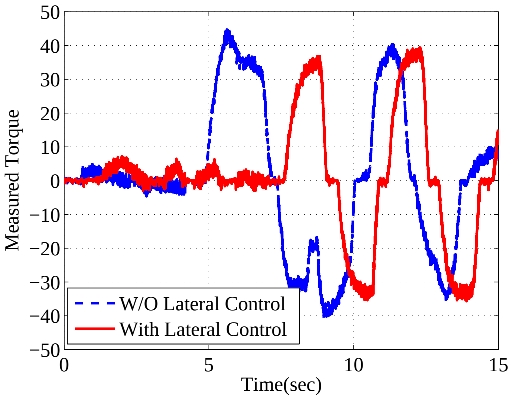

Fig. 10. Exerted Lateral Disturbances

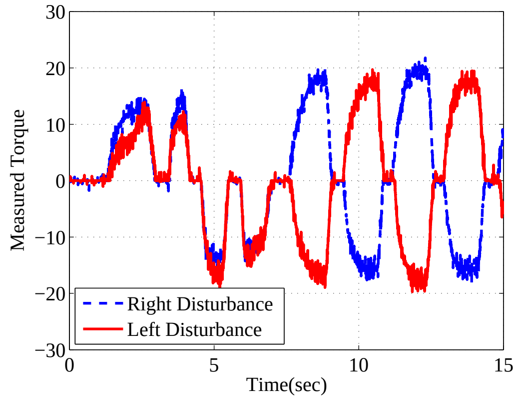

Fig. 12. Disturbances in the Same and Opposite Directions

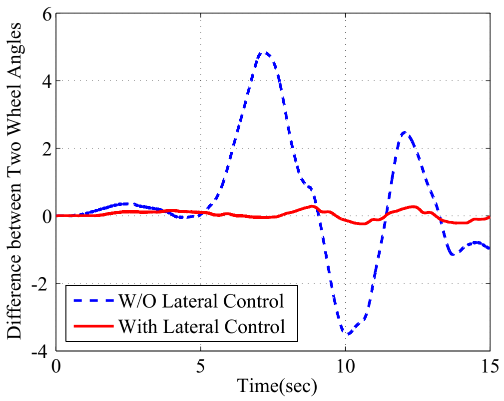

Fig. 11. Differences between the Right and Left Wheel Angles

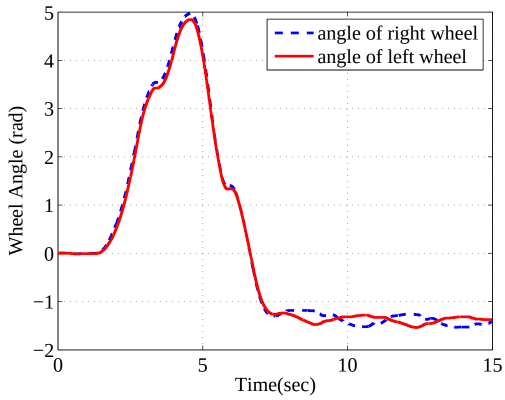

Fig. 13. Dependence of the Control on the Direction: wheel angles

from 5 to 7 seconds, the torque is applied in the opposite directions, which makes the differences quite large.

Figure 11 is the outputs of this applied torque: 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.

Figure 12,13 shows that the proposed lateral control rejects only the lateral disturbance. Figure 12 is the measured disturbance. Until 7 second, both right and left disturbances are working in the same direction, which drives the wheelchair straight. Angles described in the figure 13 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 sure that our proposed controller rejects disturbances when they are applied in the opposite direction, which means that proposed controller rejects only the lateral disturbance.

III. One Hand Propulsion Using Phase Plane

This section suggests a novel controller that helps people to drive a wheelchair with one hand. Our strategy is to get some additional information from human torque exerted on the wheelchair. Propulsion with two hands can manipulate the velocity and the direction respectively. But with one hand, the direction information can not be transmitted from human to the controller easily. Some additional interfaces can be used for this direction information, but here we use the phase plane of human torque for the information transmission.

For the realization of one hand propulsion, this section deals with two problems:
1. How to get necessary lateral information on the user's intention from the human torques
2. How to design a controller that can change the direction based on the obtained lateral information.

The second problem, design of the controller is explained at first.

A. *How to Control the Wheelchair to Go Straight or Turning*

Necessary actions to keep the wheelchair straight in spite of unbalanced human torque are
1. To provide the same assisting torque based on the measured human torque

2. To remove the effect of lateral disturbances.

A controller described in the figure 14 is adopted to realize these actions.

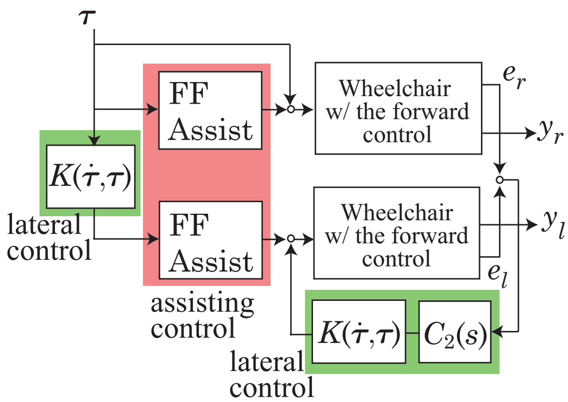

Fig. 14. Controller with the Synchronization Function $K(\dot{\tau}, \tau)$

At first, let's consider the case when $K(\dot{\tau}, \tau)$ is 1. Then the same torque is given to the feedforward assisting controller, which will provide the wheelchair with the same assisting torque. $C_2(s)$, here, is the controller which was proposed in section II-B, and will remove any lateral disturbances. From these things, we can see that if $K(\dot{\tau}, \tau)$ is 1, the controller operates in such a way that it will make the wheelchair go straight.

On the other hand, if $K(\dot{\tau}, \tau)$ is zero, the controller will not work in this way. If $K(\dot{\tau}, \tau)$ is zero, all the controls that drives the wheelchair goes away. It is certain that this zero K will make the wheelchair turn. Decision of this K between 0 and 1 will achieve the one hand propulsion.

Then how should we decide this K? There can be various ways to decide this K, such as using special interfaces and so on. But in this paper, we adopt the function of $\dot{\tau}$ and τ as this K.

B. Measurement and Analysis of Human Torque

We measured human torques, for the observation of that torques will help us in patternizing the human torque. Figure 15 is human torque described in the phase plane. The x-axis is the magnitude of the torque and the y-axis is that of the differentiated torque.

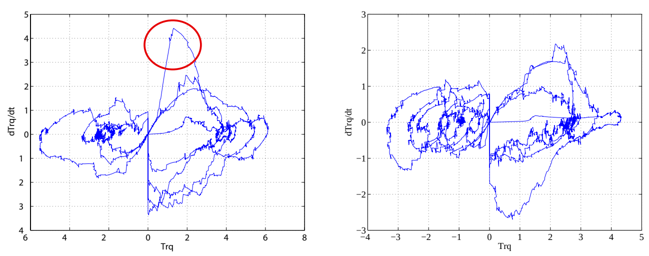

Fig. 15. Examples of Torque Pattern

This phase plane tells that the operator adjusts not only the magnitude of torque but also the ratio of change. Using this additional information, human can transmit his will to the controller.

C. Definition of Torque Patterns for Each Movement

The torque plane is divided into two segments: straight-going mode and turning mode. Figure 16 shows this division.

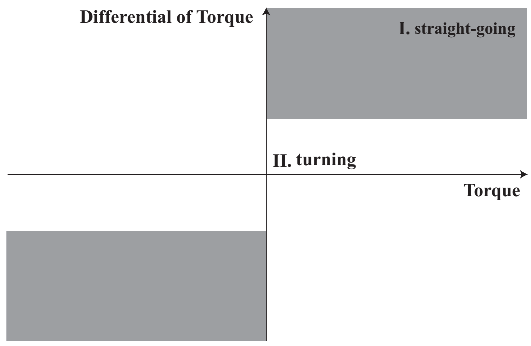

Fig. 16. Division of the Torque Phase Plane for One Hand Propulsion

The location of human torque in the phase plane decides whether the wheelchair will goes straight or turn: If the differentiated torque is in the straight-going segment, the controller will drive both wheels at the same speed, and if it is in the turning mode, the controller will assist only one wheel.

Note that this division is not two-valued logic, but gradual. Otherwise, the user can feel that his operation is not continuous and awkward. The two segments are connected in the fuzzy way. Then how that fuzzy division is implemented in the controller?

This can be realized adopting $K(\dot{\tau}, \tau)$ that is changed in the way of the equation (8).

$$K(\dot{\tau}, \tau) = \mathrm{sgn}(\tau)\frac{1}{1 + e^{-\beta(\dot{\tau}-\dot{\tau}_0)}} \tag{8}$$

With this $K(\dot{\tau}, \tau)$, experiments are done.

D. Experimental Results

Figure 17 and 18 are the experimental results. Figure 17 shows $\dot{\tau}$ and K as the function of $\dot{\tau}$ and τ. For convenience, the value of K is 30 times the real value. K is changed according to $\dot{\tau}$. K will be 1 if $\dot{\tau}$ goes over 30. Once K becomes 1, the value will be held on until the velocity of the wheelchair and the torque τ become 0 which means that the wheelchair stops. In the figure 17, around 8 second, K becomes 1, and this will make two wheels synchronize.

Figure 18 is the angles of the right and left wheels. Until 8 second, only the right wheel moves and it makes the wheelchair turn. After 8 second, the wheelchair goes into the straight-going mode for $\dot{\tau}$ goes over 30, and the right and left wheels turn at the same velocity.

This is a simple experiment, but we can see that using this controller, the user can change the direction of the wheelchair by adjusting his torque.

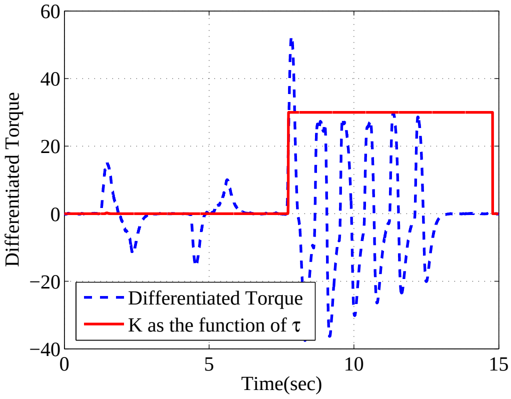

Fig. 17. $\dot{\tau}$ and $30K(\dot{\tau}, \tau)$

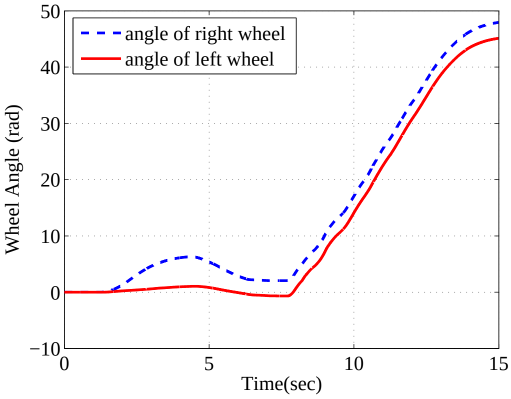

Fig. 18. Wheel Angles as the One Hand Propulsion Control Result

IV. Conclusion

This paper has proposed two lateral controls for the power assisting wheelchair. The first one was the lateral disturbance rejection control. This control is a fundamental controller for the two dimensional control of the wheelchair. Furthermore, we have designed the disturbance attenuation control for the forward disturbance, and have shown that controls for the forward direction and the lateral direction can be designed respectively and the characteristics can be designed differently.

Based on the lateral control, one hand propulsion control was designed too. Whether the wheelchair would go straight or turn, can be decided easily by the synchronization function $K(\dot{\tau}, \tau)$. Adjusting this K between 0 and 1, the direction can be controlled. We adopted a function of $\tau, \dot{\tau}$ as this K. This is only one attempt, and there can be other decisions of K. In any cases, by changing K according to some information will this one hand propulsion. Our suggestion of utilizing the differentiated torque is one intuitive way of considering one's intention, although it is a problem to solve whether this method is the most natural way for human or not.

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