Control Developments for Wheelchairs in Slope Environments

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***Abstract*— We have developed an observer and controllers for wheelchairs in slope environments in this paper.**

We select two problems that frequently happen in power-assisted wheelchair caused by gravity. The first problem lies in overturning of wheelchairs and the second problem occurs when the difficulty happens in propulsion of wheelchairs on a hill. The former is related to the observation problem, and the latter is related to the control problem. We would like to propose solutions to the both problems.

The observer, which we would like to propose here can estimate three main physical values; (1)the speed of the wheelchair,(2) the leaning angle of the wheelchair body from the ground, and (3) external disturbances. The observer can sensorfuse the informations from three sensors, which it uses the kalman filter theory.

In order to prevent the problem of the wheelchair's overturning, assistive power by the motor attached to the wheelchair should be decreased according to the state of the wheelchair concerning the leaning angle and its anglular velocity. By this, it can realized by using the proposed observer and varying assistance-ratio controller.

Key Words* : *kalman filter, multisensor, two-degree-of-freedom control, power-assisted wheelchair, gravity compensation, compliance control

I. Introduction

Nowadays advanced power assistance tools are drawing people's attention as emerging control application. These tools are usually located near a man or attached to one's body amplify human power. This operational environment is unique to these tools and makes the control of these difficult. Though a variety of power assistance tools are being developed, there is little discussion on control methods for these tools.

A power-assisted wheelchair is a good example of that kind of assistance tools. Development of controllers for a power-assisted wheelchair has just started[1]. In conventional power-assisted wheelchairs, motors just multiply original human force by up to several times. But, when a wheelchair goes on a hill, assisting motors can worsen the maneuverability.

The wheelchair needs different type of assisting power when it is on a slope, but conventional controllers do not consider the slope of ground. This can make dangerous situation such as overturning of the wheelchair or increasing the speed when the wheelchair goes down a hill.

To prevent these problems, assistance system should distinguish the road condition and identify the states of the wheelchair. But how can the controller sense all these information? We will pick up this problem in Section II and IV.

Fig. 1. Power-assisted Wheelchair as an Example of Power Assistance Tools (YAMAHA JW II)

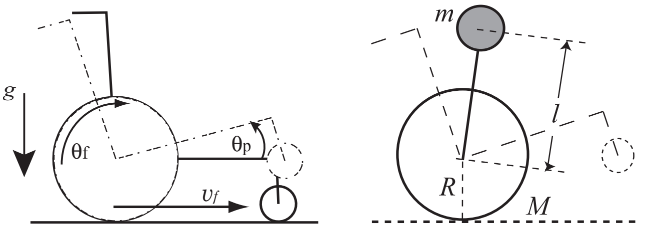
Based on these obtained information, assisting power will be modified in order to prevent overturning. These controller design problems are explored in Section III and IV.

In Section IV, a gravity compensation controller is suggeted. We adpot the two degree of freedom controller for this problem.

II. Development of Observer for Identifying of the States of Wheelchair

There are some important physical values when one drives a wheelchair, such as driving speed(v_f in figure 2 (a)) and inclination angle(θ_p in figure 2 (a)). The driving speed v_f means the speed of the whole wheelchair and it is in a paralle direction with the ground, which is illustrated in figure 2 (a). Inclination angle is the leaning angle of the wheelchair frame from the horizon. If the wheelchair is on a level ground this angle becomes zero, but if the wheelchair is on a slope or the frame of the wheelchair is inclined against the ground, this angle has non-zero value.

This inclination angle can be located in a phase plane, and the location of this angle denotes the stability of the wheelchair. If a controller can use the value, it will make the rider feel comfortable even when the wheelchair is on a hill. Encoders usually measure the driving speed. It should be noted that the wheelchair repeats low speed drivings and stops. Speed measurements at low or zero speed are liable to be noisy and incorrect when we use encoders for measurements. But correct and good estimation of this driving speed is necessary for a feedback control.



(a) states of wheelchair (b) inverted pedulum model

Fig. 2. Physical Values Needed for Control

An observer that observes these two values is developed here.

A. Observer Design Using Kalman Filter Theory

In order to design the required observer, states in equation (1) are adopted. ω_p, ω_f are the velocites of θ_p, θ_f. θ_p is the inclination angle explained previously. θ_f is the rotated angle of a wheel. Driving speed v_f can be calculated by $v_f = R\omega_f$ ignoring slips on wheels (R is the radius of the wheel). Lastly d_p, d_f are the disturbances exerted on θ_p, θ_f respectively.

$$x = \begin{pmatrix} \omega_p & \omega_f & \theta_p & \theta_f & d_p & d_f \end{pmatrix}^T \quad (1)$$

Motion equations of these states are shown in equation (2).

$$J_f\ddot{\theta}_f = -B_f\dot{\theta}_f + \tau_f + d_f, J_p\ddot{\theta}_p = -B_p\dot{\theta}_p + d_p, v_f = R\theta_f \quad (2)$$

J_f, J_p, B_f, B_p are inertias and dampings in each state. τ_f is the torque to propel the wheel, and it is exerted by human or motor. This equation uses disturbance terms to simplify the equation. The input torque to θ_p is set as 0, and θ_p is excited only by disturbance d_p. This enables us to ignore the restriction by the connection between θ_p and θ_f.

Equation (3) and (4) show detailed form of these equations. These equations are derived based on the inverted pendulum model

$$\begin{aligned} \tau_f + d_f &= \{(M+m)r + J_M\}\ddot{\theta}_f - mlr\ddot{\theta}_p\cos\theta_p \\ &\quad + mlr\dot{\theta}_p^2\sin\theta_p + B_M\dot{\theta}_f \quad (3) \\ d_p &= \left(J_m + ml^2\right)\ddot{\theta}_p - mlr\ddot{\theta}_f\cos\theta_p - mgl\sin\theta_p \\ &\quad + B_m\dot{\theta}_p \quad (4) \end{aligned}$$

M is the weights of wheels of wheelchair and m is the weight of the body including a rider. l is the distance of the center of gravity of the body from the axis of wheels. g is the gravity acceleration (See figure 2 (b)). We can notice that the former motion equations are in extremely simplified forms using the disturbances d_f, d_p compared with the latter equations.

[4] shows that these two types of equations does not make any difference in estimation. In this paper, simplified equation (2) is employed.

Three sensors (encoder, gyroscope, accelerometer) are used for measurements. Output equations are shown in Table (II-A).

The measurements a_x, a_y in the accelerometer is described in figure 3. a_x should be linearized to be utilized in the kalman filter. This results in the output equation for the observer shown in equation (5).

TABLE I

OUTPUT EQUATION OF EACH SENSOR

Encoder	$y_{\text{enc}} = \theta_f$
Gyroscope	$y_{\text{gyro}} = \omega_p$
Accelerometer	$y_{\text{acc}_x} = R\dot{\omega}_f\cos\theta_p + g\sin\theta_p$
	$y_{\text{acc}_y} = g\cos\theta_p - R\dot{\omega}_f\sin\theta_p$

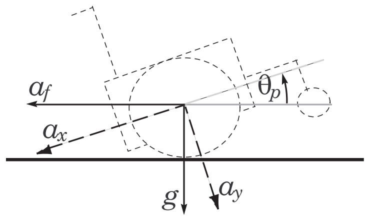


Fig. 3. Accelerations measured by accelerometer

$$\begin{aligned} y &= \begin{pmatrix} \omega_p & \theta_f & a_x \end{pmatrix}^T \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -\frac{BR}{J} & g & 0 & 0 & \frac{R}{J} \end{pmatrix} x + \begin{pmatrix} 0 \\ 0 \\ \frac{R}{J} \end{pmatrix} u \quad (5) \end{aligned}$$

The observer has three outputs, which makes the decision of observer gain not so simple. We adopted the kalman filter method for the calculation of the observer gain.

This kalman filter provides sensor fusion with the noise covariance matrix as adjustable parameter. The noise covariance data for the determination of the observer gain are like below.

$$\begin{aligned} \mathbf{Q}_x &= \text{diag}\left(Q_{\omega_p}, Q_{\omega_f}, Q_{\theta_p}, Q_{\theta_f}, Q_{d_p}, Q_{d_f}\right) \quad (6) \\ \mathbf{R}_y &= \text{diag}\left(R_{\text{gyro}}, R_{\text{enc}}, R_{\text{acc}}\right) \quad (7) \end{aligned}$$

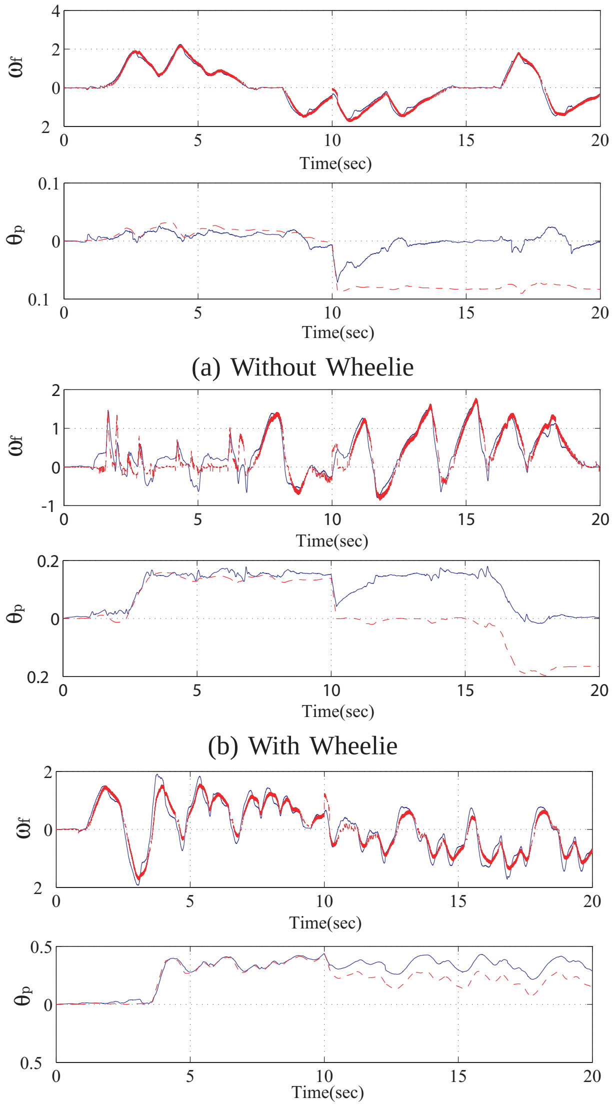
As $Q_{\omega_f}, Q_{\theta_f}$ become smaller, the noise in the estimated $\hat{\omega}_f$ becomes smaller. The same is for $Q_{\omega_p}, Q_{\theta_p}$, and the smaller they are, the less noise will $\hat{\theta}_p$ have. For good control performance, $\hat{\omega}_f$ should has small noise. Large R_{acc} will make the estimated states noiseless.

B. Experimental Results

Due to the limitation of sensors, the measurements of ω_f and θ_p can be incorrect. In order to get ω_f information, we should differentiate the encoder output discretely. If the resolution of the encoder is too low or the angular velocity of the wheel is too low, the discretely differentiated velocity will be very noisy and incorrect. To overcome this, a low pass filter is utilized, but it will make the estimation slow.

And for the measurement of θ_p, the value of a gyroscope is integrated. If there is some noise in the output of the gyroscope, the drift phenomenon will occur.

Proposed observer can overcome these two problems. Experimental results shown in figure 4 explain this point. Each figure shows ω_f and θ_p respectively. In (a), the wheelchair runs straightly on a level ground, while in (b) there is a



(a) Without Wheelie

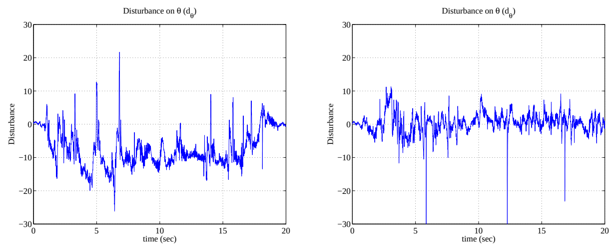
(b) With Wheelie

(b) With Wheelie

Fig. 4. Estimated States: $\hat{\omega}_f$ and $\hat{\theta}_p$

wheelie around 4 sec. (c) shows the result of experiment on a slope. The red line in the upper figure of each experiment which shows ω_f, is the low pass filtered differential of the encoder output. This value is very noisy and delayed, while the estimation of the proposed observer (blue line) is fast and not noisy. To investigate the robustness of proposed observer, we added a noise to the gyroscope output at 10 sec. Let's see the below figure of each experiment. This shows the estimated θ_p. Compared to the integration of the gyroscope output (red line in the below figure of each experiment), the proposed observer estimation (blue line) shows robust observation results. From this experimental result, we can conclude that using the proposed observer, the drift phenomenon can be avoided and better velocity information will be obtained.

We can identify the states of the wheelchair using this estimated θ_p, and apply this information to the control. But the inclination angle is not sufficient to tell whether it is on a slope or during a wheelie. d_f will tell this information. Figure 5 is the estimated d_fs. The left figure is $\hat{d}_f$ on a slope, and the right is $\hat{d}_f$ during a wheelie.



(b) With Wheelie (b) With Wheelie

Fig. 5. Estimated States: $\hat{\omega}_f$ and $\hat{\theta}_p$

If the wheelchair is on a slope, the gravity act as a disturbance to driving, but if the wheelchair is during a wheelie, it is not. Using this $\hat{d}_f$, more classified identification of the wheelchair states is available.

III. Power-Assistance-Ratio Control Method Based on Phase Plane Analysis

A. Fundamental method for power-assistance control

The power-assistance units amplify the manual inputs from the push rims with first order delay. The equation of power-assistance controller is

$$T_{assist} = \alpha \frac{1}{1+\tau s} T_{human}, \tag{8}$$

, where α is power-assistance-ratio, T_{assist} is the amplified torque from the push rim, T_{human} is the input torque from the push rim and τ is the time constant of first order delay. τ should be a suitable value realizing inertia for wheelchair. Therefore, τ at the beginning of propelling should be small value and that at the ending should be large.

And the behavior of this controller is shown in Fig.6.

Fig.7 shows the block diagram of power-assistance controller.

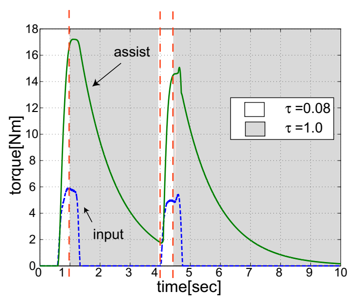


Fig. 6. Input Torque and Assistance Torque versus Time.

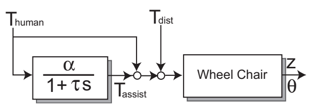


Fig. 7. Power-assisted Controller.

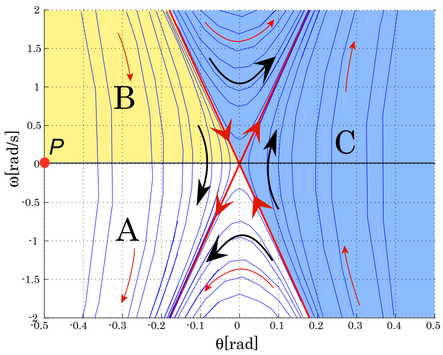


Fig. 8. Man-wheelchair Phase Plane.

B. Analysis of Overturning Using Phase Plane

Overturning of a wheelchair can be discussed with a phase plane of $\hat{\theta}_p$ and ω_p. θ_p moves according to the equation (4), so its movements can be calcuated on the phase plane using the equation.

Figure 8 shows this phase plane, 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 ($\theta_p < 0, \ \ \omega_p > 0$ and below the negative slope asymptote), and C) dangerous zone (above the negative slope asymptote).

Point P in figure 8 which denotes the state of the wheelchair, is staying generally at the point $(\theta_p, \omega_p) = (\theta_0, 0)$. But it will shift to C region through B region when the wheelchair overturns. Figure 9 show the results of manual control without power-assistance. Figure 9 shows that human operated the wheelchair successfully to return from C region.

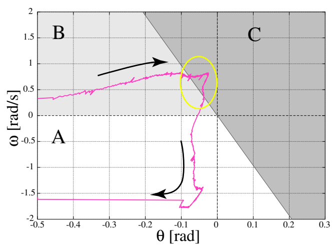


Fig. 9. θ_p in the Phase Plane during manual control

C. Design of power-assistance-ratio

Power-assistance-ratio control strategy to prevent overturning is proposed in this section. Power-assisted wheelchair tends to overturn easily on a slope because the assisting power works as overturning power on the slope. The assisting power should be decrease according to the state of θ_p. This can be achieved by modification of power-assistance-ratio. The proposed power-assistance-ratio adjustment is shown as

$$\alpha = \alpha_{max} \exp(\beta \frac{\omega_p}{\hat{\theta}_p}), \tag{9}$$

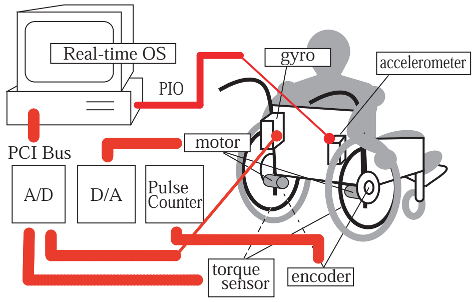
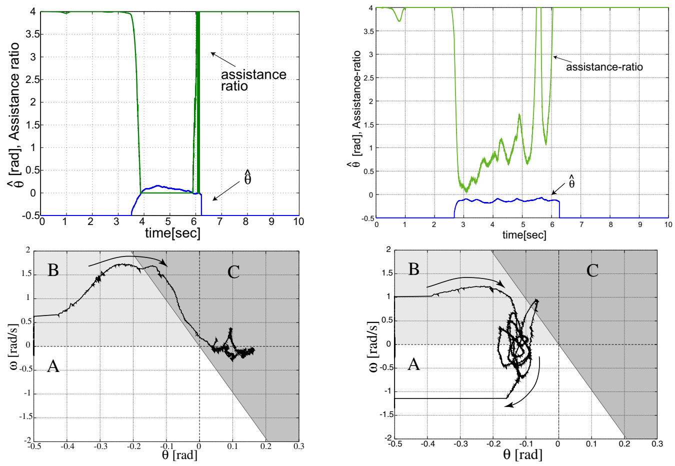


Fig. 10. Experimental Setup.



(a) $\beta = 0.5$ (b) $\beta = 3$

Fig. 11. Experimental Results.

where β is the decreasing constant which decides a speed of decreasing power-assistance-ratio. $\omega_p/\hat{\theta}_p$ implies the slope from origin on the phase plane, namely the level of danger. α_{max} is the maximum power-assistance-ratio.

D. Experiments

Figure 10 shows the setup of the experimental apparatus. Experiments with $\beta = [0.5, 3.0]$ are performed. The subject propels rims with a certain power so that it may overturn the wheelchair. The results are shown in figure 11. Figure 11(a) is done with $\beta = 0.5$, and it shows that the decrease in the assisting power is not enough and endangers the wheelchair. However, figure 11(b) which is done under $\beta = 3.0$, shows a safe front-wheel raising to get over the step on the uneven grand. β can adjust the extent of the proposed overturning prevention control and should be chosen considering the operators' preferences and driving characteristics.

IV. Gravity Compensation Controller Design

A. Flexible Disturbance Attenuation Control - Generalization of Compliance Control

Design of the disturbance response plays very important role in these power-assisting tools. These tools compensate human power against external force. Human power, however, itself can be a disturbance when it is seen from the controller. This problem is similar to the cooperation problem between robot and human, but more general.

The disturbance observer in figure 12 is a typical method of the disturbance rejection in industrial motor controls. It aims at perfect disturbance rejection up to high frequency ranges. This perfect disturbance rejection is not suitable for the power assist control. Disturbance in power assistance tools can be related to human activities in many cases. Stiff rejection of disturbance can worsen the operational performance and even make dangerous situation.

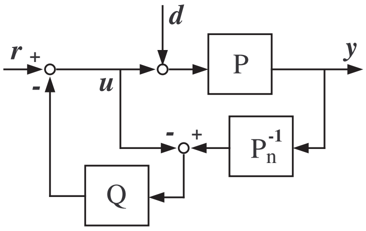


Fig. 12. The Structure of the Disturbance Observer

The disturbance attenuation should be flexible when it is applied to the power assistance tools. But the feedback in this disturbance observer is not suitable for flexible disturbance attenuation. The adjustable parameter in the disturbance observer is only suitable for the stiff rejection, and does not provide enough degree of freedom for the flexible disturbance attenuation.

B. Flexible Disturbance Attenuation Control

How can we make the disturbance attenuation flexible? As a solution we propose a feedback controller in figure 13. We can design the disturbance response arbitrarily using this feedback.

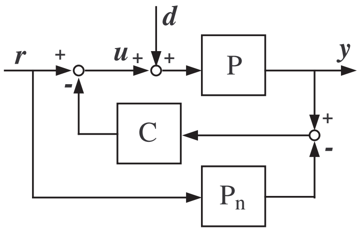


Fig. 13. Proposed Flexible Disturbance Attenuation Control

By this feedback controller, the response of the wheelchair will be :

$$y = P\left(\frac{1+CP_n}{1+CP}r + \frac{1}{1+CP}d\right). \quad (10)$$

r is a reference input and d is a disturbance. r and d are assisted torque and gravity respectively. Note that if $P_n = P$, the response by r will be Pr, which means the feedback controller does not affect this response. However the response by d is adjusted to $\frac{P}{1+CP}d$ from Pd.

The passive adaptive control in [6] has the same structure with figure 13. While [6] adopted P_n^{-1} for C to realize the perfect disturbance rejection, our proposed method decides C considering physical characteristics.

Flexible disturbance attenuation does not reject disturbance perfectly. It just modifies the physical characteristics of the plant against disturbance. This point is similar with the compliance control[7] used in robot controls. Utilizing various filters as C, we can realize various flexible disturbance attenuations, and it will provide enough degree of freedom.

We will design a gravity compensation controller as one example of this flexible disturbance attenuation in next section.

C. Necessity of Gravity Compensation in the Power-assisted Wheelchair

Propulsion of a wheelchair on a slope is heavier burden than on level ground. Figure 14 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 assist control is more necessary on hills. However, many of commercial power-assisted wheelchairs do not assist the propulsion on hills because of difficulties of control. Furthermore, as discussed the previous section, inadequate power assistance can make the wheelchair unstable.

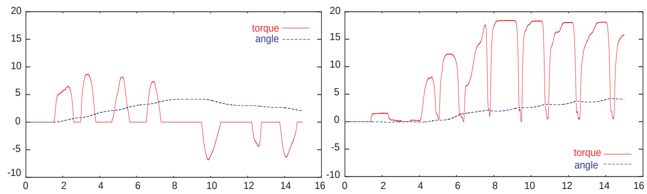


Fig. 14. Necessary torques to drive a wheelchair (Upper: drive on level ground, Lower: drive on hill)

D. Flexible Gravity Attenuation Control

Figure 15 shows the structure of proposed gravity attenuation controller. The TDOF controller using proposed flexible disturbance attenuation is applied.

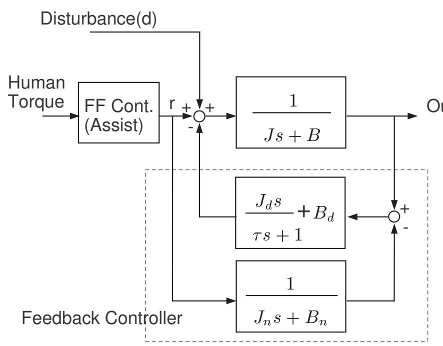


Fig. 15. Structure of flexible gravity attenuation controller applied to a power-assisted wheelchair

$\frac{1}{Js+B}$ is the dynamics of the wheelchair, and ”FF Cont.(Assist)” means a feedforward controller for a power assistance which was introduced in section III-A. Controller in the dotted rectangular is the gravity compensation controller.

Increasing the friction and inertia of the wheelchair makes the wheelchair seem heavy to gravity. Here, zero stiffness ($K_d = 0$) is employed for it will produce just a certain amount of power to attenuate the effect of gravity on the wheelchair. The amount can be modified arbitrarily based on the inertia and friction of the wheelchair changed by the filter C. To this end, we adopt $J_d s + B_d$ as C, and it will change like follows:

$$\frac{1}{Js+B} \rightarrow \frac{1}{(J+J_d)s+(B+B_d)}. \qquad (11)$$

E. Experimental verification of proposed method

The effectiveness of this gravity compensation controller are verified by experiments using the same experimental setup in figure 10.

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 16. 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.

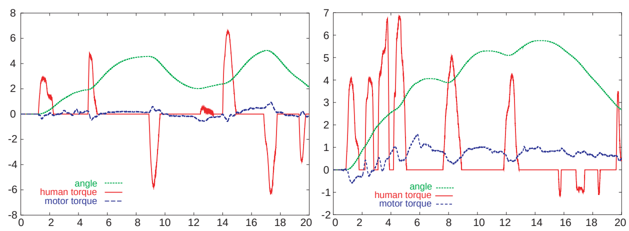


Fig. 16. Experimental Results (Left: drive on level ground, Right: drive on hill))

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.

F. Extention to the Compensation in the Lateral Direction

A slope in the lateral direction is troublesome for a wheelchair. The proposed controller can be extended to this problem. Figure 17 is the structure of the compensator for the gravity in the lateral direction.

Comparing the disturbances in the left and the right direction, we can assess the gravity in the lateral direction. By feedback of this gravity information, the gravity is compensated. This compensator is to be validated by experiments.

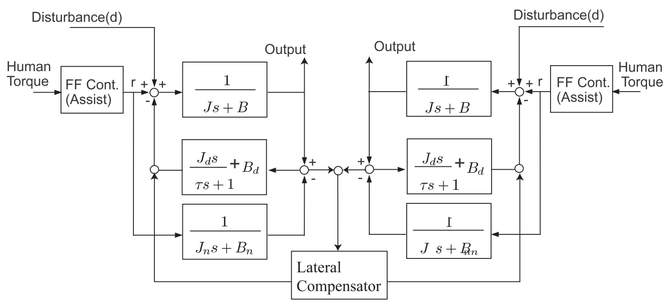


Fig. 17. Structure of Lateral Direction Gravity Compensator

V. Conclusion

In this paper, we have suggested an observer and controller for wheelchairs in slope environments.

The first suggestion was the development of observer for important physical values. The observer should be designed to make user of power assistance tools feel comfort and to adapt to various environments. The observer we proposed was an example that provides a rider safe and natural assistive control. Also we have shown that sensor fusion by the observer design method can improve the ability of sensors and make the estimation more robust to sensor noise.

The other suggestion was the flexible disturbance attenuation. It provides the TDOF control which can design the disturbance response by changing physical values of a plant, and it can make the response flexible. In the gravity compensation control, the parameters was inertia, damping. This flexible disturbance attenuation is a key when we design a controller for power assistance tools, because the stiffness to the disturbance should be modified arbitrarily.

What we have suggested in this paper showed that advanced motion control theory can improve existing power assistance systems when it is properly designed. There are many things to be discussed to establish this human-friendly motion control. This technology is notable not only from the viewpoint of engineering but also from that of society.

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