Proposal of Human-friendly Motion Control and its Application to Wheelchair

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Abstract: In this paper, we expand the human-friendly control concept which has been restricted only to the robot controls into general assistive controls. For a demonstration of this generalized human-friendly control, we adopt a power-assisted wheelchair and apply a novel control to it.
We investigate some requirements for this generalized human-friendly control and suggest solutions to it. Our solution approach consists of two parts: one is on the observation problem, the other is on the control problem.
We pick up two problems which happen in power-assisted wheelchair control by gravity. The first is the tendency of falling backward that is related to the observation problem, and the other is the difficulty in propulsion on a hill that is related to the control problem. We propose solutions to each problem, generalize them, and try to establish the human-friendly control.

Keywords: human-friendly control, gravity compensation, center-of-gravity observer, two-degree-of-freedom control, power-assisted wheelchair, flexible disturbance attenuation, compliance control

1. Introduction

Control design necessary for the development of human-friendly robots has been researched recently. These human-friendly control designs are not necessary only for robot control. They should be applied to all products that are used near people.

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, and amplify human power. This operational environment makes the control difficult and unique to these tools. Though a variety of power assistance tools are being developed, there is little discussion on control methods for those tools.

This paper proposes the human-friendly control for the control of these power assistance tools.

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

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 to drive by up to several times. But, when a wheelchair goes on a hill, assisting motors can worsen the maneuverability, because the controller of motors does not consider the slope of ground and does the same control while it is on level ground. Besides that, when a wheelchair goes down a hill, power assistance does make dangerous situation because it increases the speed.

To prevent these problems, assistance system should distinguish the road condition and know the phase of the wheelchair. But how can the controller sense all these infromation? We will pick up this sensing problem in Section 3 and 6.

In Section 2, 5 we explain what is necessary for the human-friendly control. Since discussed requirements in Section 2 are somewhat general ideas, we specialize this general ideas by realizing them in the power-assisted wheelchair control in Section 3, 4 and 6.

2. Requirements for the Human-friendly Control

The next four characteristics are the requirements for the human-friendly control.

Adaptation to the environment

The range of human activities is large. Power assistance tools used for these human activities should adapt to various environment.

Excellent operational performance

Power assistance tools are located near a man. Every movement of the tools will affect user's sense directly. So as not to make user uncomfortable, the controller should have excellent operational performance.

Flexibility to disturbance

Disturbance is defined as power which is not produced from the controller. In this meaning, human power is a disturbance for the controller, and strict rejection of this disturbance can make dangerous situation or awkward operation.

Useful evaluation of control

There are little established evaluation about how human-friendly the controller is. It is due to the difficulty in description of the performance in mathematical way.

These are the problems in the human-friendly control, and solutions to each problems will help to establish the human-friendly control. To this end, we propose some solutions here.

The observer design technology can play important roles to improve the adaptation and operation performance of power assistance tools. There are more physical values that should be controlled in human-friendly control compared with the conventional industrial control. Those physical values which we want to use control can be obtained using various observers.

In industrial controls, disturbances should be rejected perfectly up to high frequency bandwidth. This strategy is not suitable for these power assistance tools. Disturbance attenuation should be more flexible. There is compliance control in robot controls for flexible disturbance rejection, but it has lots of things to be discussed to be applied to general power assistance tools.

For this generalization towards other assistance tools, we propose a flexible disturbance attenuation control in Section 5. The design of disturbance response is strongly related to the human-friendly control. More freedom of degree in disturbance attenuation control makes the control human-friendly. In Section 5 we argue more about this thing.

3. Analysis of the Phase of a Wheelchair Using a COG Observer

The center of gravity is one of the key physical values when one drives a wheelchair. Its location in the phase plane can denote the phase 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. An observer which observes the center of gravity is developed here.

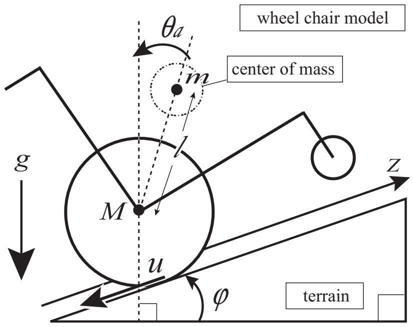


Figure 2: Model of Man and Wheelchair System.

3.1 Motion Equations Using the Inverted Pendulum

When the front wheel is raising off the ground, man-wheelchair system can be regarded as an approximate inverted pendulum model[2)] shown by Fig.2. The operator's mass is assumed to be concentrated to the COG with mass m linked to the rear wheel with distance l. And θ is the vertical angle term between the COG and the rear wheel axis. The model is controlled by force u. The motion equations of Fig.2 can be derived by Lagrange method and are denoted as

$$\begin{aligned} u &= (M+m)\ddot{z} + ml(\ddot{\theta}\cos(\varphi+\theta) - \dot{\theta}^2\sin(\varphi+\theta)) \\ &\quad +(M+m)g\sin\varphi \qquad (1) \\ 0 &= ml\ddot{z}\cos(\varphi+\theta) + ml^2\ddot{\theta} - mgl\sin\theta. \qquad (2) \end{aligned}$$

where z is the position of moving direction, and the mass around the rear wheel is concentrated to the rear wheel axis with mass M. φ is the slope angle. Input force u is the sum of the forces given by the push rims and power-assistance units.

3.2 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

$$T_{assist} = \alpha \frac{1}{1+\tau s} T_{human} \qquad (3)$$

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 as the following relations.

$$\tau = \begin{cases} \tau_{fast} & \frac{d}{dt}T_{human} > 0 \\ \tau_{slow} & \frac{d}{dt}T_{human} < 0 \end{cases}, \quad (\tau_{fast} < \tau_{slow}) \qquad (4)$$

For example, our experiments adopt the following values respectively,

$$\tau_{fast} = 0.08[s], \quad \tau_{slow} = 1.0[s]. \qquad (5)$$

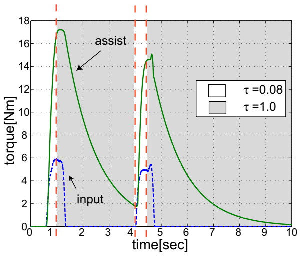


Figure 3: Input Torque and Assistance Torque versus Time.

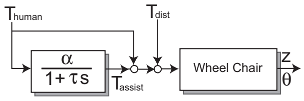


Figure 4: Power-assisted Controller.

And the behavior of this controller is shown in Fig.3.

Fig.4 shows the block diagram of power-assistance controller.

Falling backward occurs as the interaction between the position of center-of-gravity (COG) on man-wheelchair system and its angular velocity. But the position cannot be measured directly by using general sensors because operators' build types and sitting styles are widely differing. Conventional COG design methods for wheelchairs are done by static analysis based on anatomical viewpoint[3)]. Then, we propose "COG Observer" to estimate dynamically the position of COG.

3.3 Derivation of COG observer

The COG observer is derived from the linearized system such that it is consisted of the system (1),(2) around the unstable point of $(\theta, \dot{\theta}) = (0, 0)$. The linearized system around $(\theta, \dot{\theta}) = (0, 0)$ becomes the following equation.

$$\begin{pmatrix} \ddot{\theta} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} 0 & \frac{M+m}{Ml}g \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \dot{\theta} \\ \theta \end{pmatrix} + \begin{pmatrix} -\frac{1}{Ml} \\ 0 \end{pmatrix} u \quad (6)$$

Then, the output from wheelchair is defined as

$$y = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} \dot{\theta} \\ \theta \end{pmatrix}. \quad (7)$$

(7) is decided from the angular velocity of wheelchair's frame around the rear wheel axis. It is assumed that the operator's body and the frame of wheelchair rotate with the same velocity during falling backward.

The COG observer is designed based on Gopinath method [4)]. The estimated value is defined as $\hat{\theta}$. Substituting $\hat{\theta}$ for the first row of (6),

$$\dot{\hat{\dot{\theta}}} = \frac{(M+m)g}{Ml}\hat{\theta} - \frac{1}{Ml}u \quad (8)$$

is obtained. For a system of $\hat{\theta}$ with the feedback gain k of an error between $\ddot{\theta}$ and $\dot{\hat{\dot{\theta}}}$, the following equation is defined.

$$\dot{\hat{\theta}} = \dot{\theta} + k(\ddot{\theta} - \dot{\hat{\dot{\theta}}}) \quad (9)$$

In order to eliminate $\ddot{\theta}$, (9) is redefined as

$$\begin{aligned} \dot{\xi} &= \dot{\theta} - k\dot{\hat{\dot{\theta}}} - k\frac{M+m}{Ml}g \cdot k\dot{\theta} \\ &= [1 - k^2\frac{(M+m)g}{Ml}]\dot{\theta} - k\frac{(M+m)g}{Ml}\xi + \frac{k}{Ml}u. \end{aligned} \quad (10)$$

As a result, the COG observer is given by

$$\hat{\theta} = \xi + k\dot{\theta}. \quad (11)$$

3.4 Analysis of Falling Backward Using Phase Plane

In this part, the falling backward phenomenon of a wheelchair is discussed with a phase plane for $\hat{\theta}$ and $\dot{\theta}$. As mentioned above, falling backward is caused not only by the position of the COG but also by its angular velocity. Fig.5 shows man-wheelchair phase plane, which divides the plane into three regions depending on the level of danger; A) proper safety zone ($\dot{\theta} < 0$ and below the negative slope asymptote), B) semi-safety zone ($\theta < 0$, $\dot{\theta} > 0$ and below the negative slope asymptote), and C) dangerous zone (above the negative slope asymptote). Point P in Fig.5, which denotes

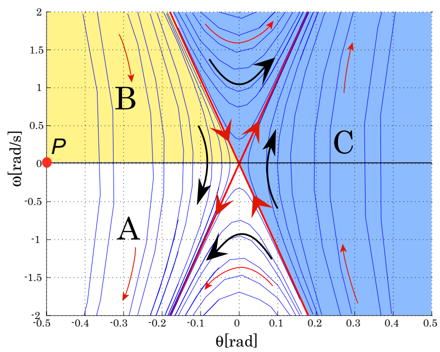


Figure 5: Man-wheelchair Phase Plane.

man-wheelchair system maneuvering, is staying generally at the point $(\theta, \dot{\theta}) = (\theta_0, 0)$. But it will shift to C region through B region when falling backward occurs. Figs.6, 7 show the result of falling backward controlled by a subject without power-assistance control. There, of course, are some offset between gyro sensor (see Fig.8)'s angle and the estimated in Fig.6. And it is shown in Fig.7 that the subject operated the wheelchair successfully to return from C region.

4. Power-assistance-ratio Control Method based on Phase Plane Analysis

4.1 Design of power-assistance-ratio

Power-assistance-ratio control strategy for falling backward is proposed in this section. Power-assisted wheelchair should be controlled by the operator to be some extent from a viewpoint of secure feeling, hence we

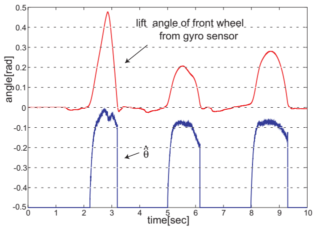


Figure 6: Estimated Angle $\hat{\theta}$ and Integral of Gyro Sensor's Output.

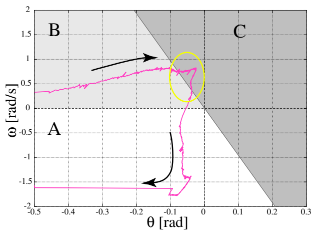


Figure 7: Phase plane of Fig.6.

aim at realization of falling backward compatible controller with operations. The proposed power-assistance-ratio adjustment is shown as

$$\alpha = \alpha_{max} \exp(\beta \frac{\dot{\theta}}{\hat{\theta}}), \tag{12}$$

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

4.2 Experiments

Fig.8 shows the construction of the experimental apparatus. Experiments with $\beta = [0.5,\ 3.0]$ are performed that the subject propels rims so that falling backward would occur intentionally. The results are shown in Fig.9. Fig.9(a), in case of $\beta = 0.5$, denotes a dangerous incident that the operator can no longer get up himself, however, Fig.9(b), in case of $\beta = 3.0$, denotes a safe front-wheel raising to get over the step on the uneven grand. β can adjust the extent of falling backward control and should be chosen considering the operators' preferences and driving characteristics.

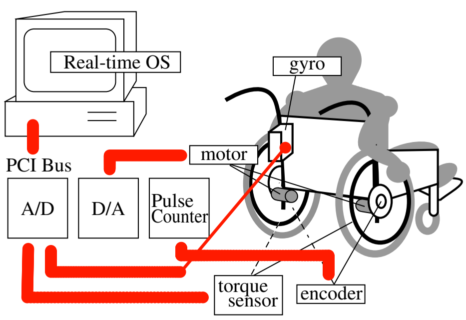
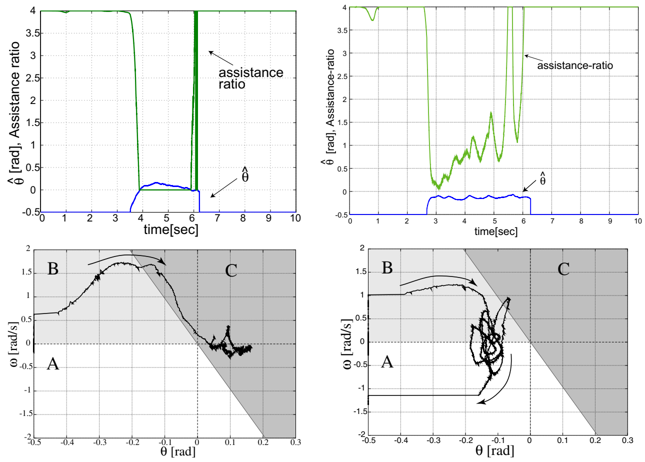


Figure 8: Experimental Setup.



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

Figure 9: Experimental Results.

5. Flexible Disturbance Attenuation Control - Generalization of Compliance Control

As we explained in Section 2, the design of the disturbance response plays very important role in the human-friendly control. Power assistance tools compenaste 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.

5.1 Disturbance Attenuation Problem Unique to Power Assistance Tools

The disturbance observer in figure 10 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.

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.

5.2 Flexible Disturbance Attenuation Control

How can we make the disturbance attenuation flexible? As a solution we propose a feedback controller in figure 11. We can design the disturbance response arbitrarily using this feedback.

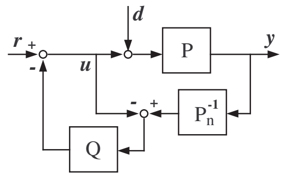


Figure 10: The Structure of the Disturbance Observer

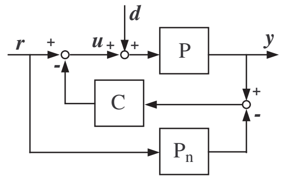


Figure 11: Proposed Flexible Disturbance Attenuation Control

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

$$y = P\left(\frac{1+CP_n}{1+CP}r + \frac{1}{1+CP}d\right). \qquad (13)$$

r is a reference input and d is a disturbance, which 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.

This is the very feature of the two-degree-of-freedom (TDOF) control [6]. The TDOF controller designs the input response and the disturbance response separately. Conventional TDOF control design such as [6] uses the disturbance observer for the design of the disturbance response. But, using proposed controller, we can design a TDOF controller with flexible disturbance attenuation.

The passive adaptive control in [7] has the same structure with figure 11. While [7] 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[8] 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.

6. Gravity Compensation Controller Design

6.1 Necessity of Gravity Compensation in the Power-assisted Wheelchair

Propulsion of a wheelchair on a hill is heavier burden than on level ground. Figure 12 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, which means on hills, the power assist control is more necessary. However, many of commercial power-assisted wheelchairs do not assist the propulsion on hills because of difficulties of control.

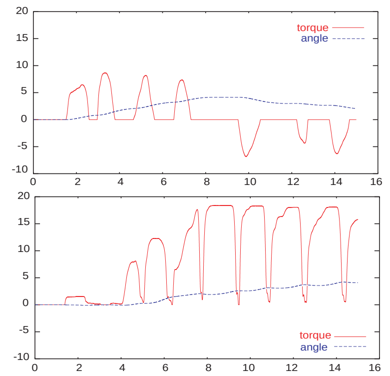


Figure 12: Necessary torques to drive a wheelchair (Upper: drive on level ground, Lower: drive on hill)

On a hill, a wheelchair will be tilted and its center of balance will shift to the unstable area. This is a problem of the power assist control of a wheelchair on a hill. Inadequate power assistance makes the wheelchair unstable and fall backward, because assisting power will work in the same direction with gravity.

6.2 Flexible Gravity Attenuation Control

Figure 13 shows the structure of proposed gravity attenuation controller. The TDOF controller using proposed flexible disturbance attenuation is applied.

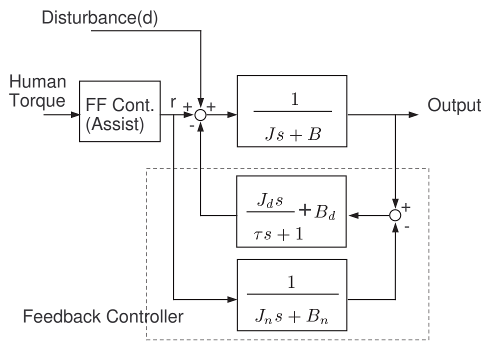


Figure 13: Structure of flexible gravity attenuation controller applied to a power-assisted wheelchair

$\frac{1}{Js+B}$ is the dynamics of the wheelchair, and "FF Cont.(Assist)" means a feedforward controller for a power assistance which will be $\frac{K}{\tau_f+1}$, where K is an assistance ratio. 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. This can be flexible gravity attenuation. The controller 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 from equation (14) to (15).

$$\frac{1}{Js + B} \tag{14}$$

$$\frac{1}{(J + J_d)s + (B + B_d)} \tag{15}$$

6.3 Experimental verification of proposed method

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

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 14. 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.

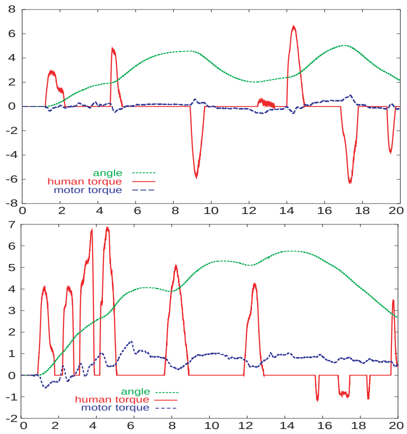


Figure 14: Experimental Results (Upper: drive on level ground, Lower: drive on hill))

7. Conclusion

In this paper, we suggested the human-friendly control. Some requirements for this human-friendly control were listed and we proposed solutions to those requirements. The solutions are applied to a power-assisted wheelchair control.

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 COG observer we proposed was an example that provide a rider safe and natural assistive control.

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 control. However, this technology is notable not only from the viewpoint of engineering but also from that of society.

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