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A Stabilization Control of Two Wheels Driven Wheelchair

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Abstract— **The paper describes a stabilization control of two wheels driven wheelchair based on pitch angle disturbance observer (PADO). PADO makes it possible to stabilize the wheelchair motion and remove casters. This brings a sophisticated mobility of wheelchair because the casters are obstacle to realize step passage motion and so on. The proposed approach based on PADO is robust against disturbance of pitch angle direction and the more functional wheelchairs is expected in the developed system. The validity of the proposed method is confirmed by simulation and experiment.**

I. INTRODUCTION

Population aging is rapidly progressing in many countries. It is reported that Japan, Italy, and Germany have the highest ratio for the population over 65 years old, whose percentages are 21.0%, 20.0%, and 18.8%, respectively. The problem of aging is said to become more serious in the future. Moreover, many people are expecting that technological breakthrough will bring them benefit and enrich their lives. Various welfare devices have been developed for elderly and handicapped people influenced by such social circumstances. Among those devices, wheelchairs are being widely used in daily lives by people with difficulty in walking. A broad range of studies have been made on intelligent wheelchairs, such as improvement of operation performance by considering haptic interaction or running environment. In the practical application, however, wheelchairs with casters are not suitable for step passage motion. This is a big obstacle to expand wheelchair utilization.

Several researches about wheelchairs to improve the environment adaptability have been performed until now. Seki et al. have proposed control methods for wheelchairs on circular roads based on balanced assisted torque [1] and fuzzy algorithm [2]. Focusing on the peculiar problem for power-assisted wheelchairs that may overturn, Li proposed the control system to prevent overturn[3]. Researches about wheelie motion have been performed to go over steps by Seki and Sato and Takahashi et al.[4]-[6]. In the above researches, an application target of power assist control is a wheelchair's rider. To promote further expansion of power assist control, advanced approaches for caregivers have also been considered. Kaida has proposed a power-assist control taking curved trajectories into account [7] and Tashiro proposed a step passage control for caregivers[8].

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The more application of wheelchairs to provide support for not only elderly persons but also disabled people is expected as a functional welfare device. Therefore, a realization of the sophisticated wheelchairs is highly required in the future. In the practical development, however, there are still some structural problems of the existing wheelchairs to realize higher mobility and space saving. First, it is difficult to control a short turn motion in the wheelchairs. Three or four wheels structure causes this problem. Second, it is so hard to go over steps because of the resistance of small front wheels like casters. Third, eye levels of wheelchair's rider are lower than that of pedestrian. This makes the riders feel an inferiority complex. This problem can be improved if the seat position is higher. However, it is not desirable from a safety point of view because it has a higher risk of overturn.

This paper focuses on two wheels robots to improve the above issues. Several kinds of two wheels robot have been invented until now. Grasser proposed two wheels driven mobile robot called Joe[9]. Joe can realize not only going straight but also taking a short turn, keeping the stable attitude. Abe et al. proposed two wheels driven mobile manipulator. This robot may do some works to keep the stable attitude. PMP invented by Sasaki is the vehicle that humans can ride on[12][13]. PMP attains space saving and is powerful system. However PMP's expected users are only healthy people because riders must be standing. Some companies develop two wheels vehicles. Segway has already sold around the world as the most famous two wheels vhicle[14]. TOYOTA announces some two wheels vehicles such as winglet[15]. However, researches about wheelchair type of two wheels vehicles are very few.

In this paper, a new type of wheelchair with two wheels structure, that is, two wheels driven wheelchair is described. The proposed wheelchair consists of right and left in-wheel-motors and main body in which riders can sit. It has no casters, that is, caster-less wheelchair system. It makes possible to solve the structural problems of the existing wheelchairs and achieve higher mobility and space saving. The overview of two wheels driven wheelchair is shown in Fig. 1.

As shown in Fig.1, two in-wheel-motors are attached on right and left side of main body respectively. Also gyro sensor is mounted to measure pitch angle and angular velocity. This wheelchair motion is like an inverted pendulum motion. This means that there is a fatal structural problem from a safety point of view. To improve this issue, stability control of wheelchair attitude is indispensable.

This paper proposes a robust control strategy to realize stable attitude motion of wheelchair. There are two remark-

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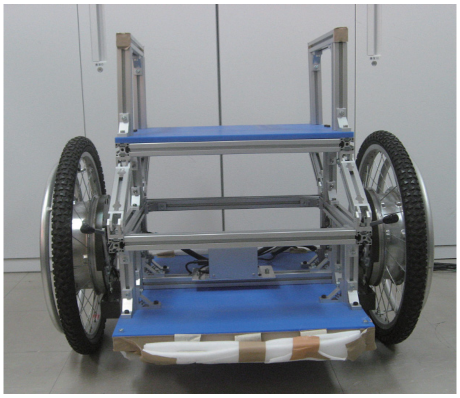
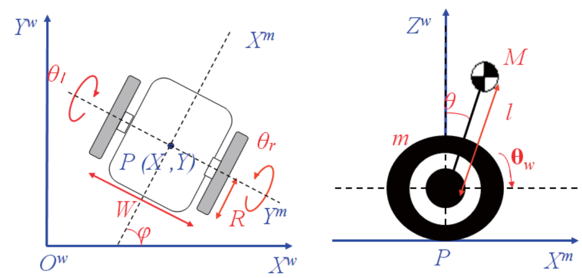


Fig. 1. Overview



(a) Top view. (b) Side view.

Fig. 2. Modeling of two wheels driven wheelchair.

able features in the proposed approach. First, disturbance of pitch angle direction is estimated by Pitch Angle Disturbance Observer (PADO). PADO may estimate the disturbance of pitch angle direction including the modeling error by using pitch angular velocity response and right/left angular velocity response. Generally, it is difficult to obtain the rigorous modeling of two wheels driven wheelchair considering wheelchair's rider. The feedback of the estimated disturbance by PADO realizes the compensation of disturbance such as gravity, friction, centroid fluctuation and mass variation. Second, the stability of the proposed control system is proved by Lyapunov stability theorem. Then the control input is determined based on Lyapunov stability theorem using PADO.

The contents of this paper are as follows: In section II, the dynamic model of two wheels driven wheelchair is introduced. In section III, a stabilization control based on PADO is described. Sections IV and V show simulation and experimental results to verify the validity of the proposed approach. Finally, conclusion and future works are described in section VI.

II. MODELING

This section shows a modeling of two wheels driven wheelchair. Also kinematics and dynamics of the wheelchair are described.

A. Modeling of Two Wheels Driven Wheelchair

An illustration of wheelchair is shown in Fig. 2[16][11]. Fig. 2(a) and (b) show top view and side view respectively. Here superscript w means world coordinate and superscript m means wheelchair's coordinate. As shown in Fig. 2(b), the motion of the proposed wheelchair is described as one inverted pendulum system. The center point of the wheel axle P is the position reference point. The nomenclature is summarized in Table I.

Position vectors $\boldsymbol{X}$ and $\boldsymbol{\theta}$ are defined as eq.(1) and eq.(2) respectively in each coordinate.

$$\boldsymbol{X} = \begin{bmatrix} X & Y & \phi & \theta \end{bmatrix}^T \tag{1}$$

$$\boldsymbol{\theta} = \begin{bmatrix} \theta_r & \theta_l & \theta \end{bmatrix}^T = \begin{bmatrix} \boldsymbol{\theta}_w & \theta \end{bmatrix}^T \tag{2}$$

TABLE I
VARIABLES FOR THE WHEELCHAIR

W	The tread of the wheelchair
R	The radius of the wheel
M	Total mass without the wheels and base
m	Mass of the wheels and base
l	Distance from center of the wheel to center of the gravity
θ_r, θ_l	The rotation angle of the right/left wheel
$\boldsymbol{\theta}_w$	The rotation angle vector that represents θ_r and θ_l
θ	Inclination of the wheelchair (pitch angle)
X, Y	Position of the wheelchair in world coordinate
v	running velocity
ϕ	The direction angle of the wheelchair

B. Kinematics

From Fig. 2, the kinematics of wheelchair is derived in eq.(3) under the following two assumptions.

- Two wheels driven wheelchair has no motion in the lateral direction.
- Both right and left wheels have no slip.

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{R}{2}\cos\phi & \frac{R}{2}\cos\phi & 0 \\ \frac{R}{2}\sin\phi & \frac{R}{2}\sin\phi & 0 \\ \frac{R}{W} & -\frac{R}{W} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta}_l \\ \dot{\theta} \end{bmatrix} = \boldsymbol{J}_{aco}\dot{\boldsymbol{\theta}} \tag{3}$$

Here $\boldsymbol{J_{aco}}$ is called Jacobian matrix. Using the pseudo-inverse matrix of $\boldsymbol{J}^+_{aco}$, the inverse kinematics is given in

$$\begin{bmatrix} \dot{\theta}_r \\ \dot{\theta}_l \\ \dot{\theta} \end{bmatrix} = \frac{1}{R}\begin{bmatrix} \cos\phi & \sin\phi & \frac{W}{2} & 0 \\ \cos\phi & \sin\phi & -\frac{W}{2} & 0 \\ 0 & 0 & 0 & R \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix} = \boldsymbol{J}^+_{aco}\dot{\boldsymbol{X}}. \tag{4}$$

The above relations are used to realize the wheelchair motion in simulation.

C. Dynamics

As shown in eq.(5), motion equation of two wheel driven wheelchair is obtained by Lagrange's equation.

$$\boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{H}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{G}(\boldsymbol{\theta}) = \boldsymbol{\tau} \tag{5}$$

Where,

$$\boldsymbol{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$
$$= \begin{bmatrix} \frac{(m+M)R^2}{4} + J_w + C & \frac{(m+M)R^2}{4} - C & \frac{M}{2} lR\cos\theta \\ \frac{(m+M)R^2}{4} - C & \frac{(m+M)R^2}{4} + J_w + C & \frac{M}{2} lR\cos\theta \\ \frac{M}{2} lR\cos\theta & \frac{M}{2} lR\cos\theta & Ml^2 \end{bmatrix}$$

$$\boldsymbol{H} = \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} = \begin{bmatrix} 2\frac{MR^2l^2}{W^2}\sin\theta\cos\theta(\dot\theta_r - \dot\theta_l)\dot\theta - \frac{MlR}{2}\sin\theta\dot\theta^2 \\ 2\frac{MR^2l^2}{W^2}\sin\theta\cos\theta(\dot\theta_r - \dot\theta_l)\dot\theta - \frac{MlR}{2}\sin\theta\dot\theta^2 \\ \frac{MR^2l^2}{W^2}\sin\theta\cos\theta(\dot\theta_r - \dot\theta_l)^2 \end{bmatrix}$$

$$\boldsymbol{G} = \begin{bmatrix} G_1 \\ G_2 \\ G_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -Mgl\sin\theta \end{bmatrix}$$

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_r \\ \tau_l \\ T_3 \end{bmatrix} \qquad \boldsymbol{\theta} = \begin{bmatrix} \theta_r \\ \theta_l \\ \theta \end{bmatrix}$$

Here $C = \frac{JR^2}{W^2} + \frac{MR^2l^2}{W^2}\sin^2\theta$. J is the inertia of wheelchair about vertical axis through P. J_w is the inertia of each driving axle. The above relations are utilized for simulation and controller design.

III. CONTROLLER DESIGN

In this section, a robust control system to realize stable attitude of two wheels driven wheelchair is proposed. First, disturbance in pitch angle direction is defined. Second, Pitch Angle Disturbance Observer(PADO) is proposed. Finally, a stabilization control based on both PADO and Lyapunov's stability theorem is constructed.

A. Motion Equation in Pitch Angle Direction

As described before, two wheels driven wheelchair is an unstable vehicle in the pitch angle direction. To design the stabilization controller of pitch angle response, the motion equation of pitch angle direction is introduced. From eq.(5), it is given as follows.

$$M_w(\ddot\theta_r + \ddot\theta_l) + M_{33}\ddot\theta + G_3 + H_3 = T_3 - T_3^{dis} \qquad (6)$$

Here M_w is an equivalent mass in the pitch angle motion. The input torque T_3 is zero because the pitch angle direction has no actuators, that is, is regarded as passive joint. T_3^{dis} denotes disturbance imposed on the passive joint. Then the rider's torque input is included in T_3^{dis}. Eq.(6) is rewritten in eq.(7).

$$\begin{aligned} M_{33}\ddot\theta &= -M_w(\ddot\theta_r + \ddot\theta_l) - (G_3 + H_3 + T_3^{dis}) \\ &= -M_w(\ddot\theta_r + \ddot\theta_l) - \acute{T}_3^{dis} \end{aligned} \qquad (7)$$

Here $\ddot\theta$ and $(\ddot\theta_r + \ddot\theta_l)$ are regarded as output and input for the pitch angle motion respectively. Equation (7) is transformed into eq.(8) equivalently.

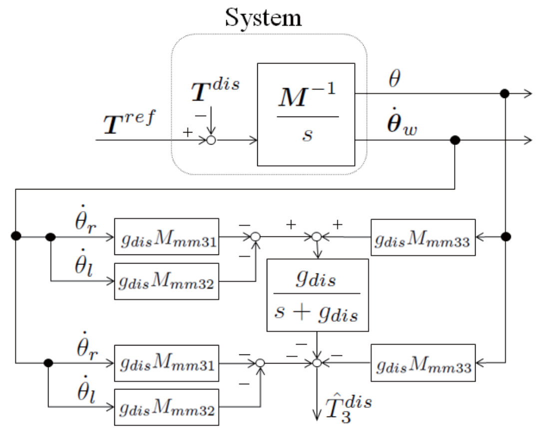


Fig. 3. The block diagram of pitch angle disturbance observer (PADO).

$$-M_{mmw}(\ddot\theta_r + \ddot\theta_l) - \{\acute{T}_3^{dis} + (\boldsymbol{M_3} - \boldsymbol{M_{mm3}})\ddot{\boldsymbol{\theta}}\} = M_{mm33}\ddot\theta \qquad (8)$$

Here $\boldsymbol{M}_{mm}$ is nominal mass matrix of pitch angle motion and $(\boldsymbol{M}_3 - \boldsymbol{M}_{mm3}$ stands for the variation of $\boldsymbol{M}_3$. $\boldsymbol{M}_{mm3}$ is third row vector of the mass matrix $\boldsymbol{M}$. As a result, $\acute{T}_3^{dis} + (\boldsymbol{M}_3 - \boldsymbol{M}_{mm3}\ddot{\boldsymbol{\theta}}$ is redefined as total disturbance $\tilde{T}_3^{dis}$ of pitch angle direction.

B. Pitch Angle Disturbance Observer(PADO)

In the proposed approach, $\tilde{T}_3^{dis}$ is estimated by pitch angle disturbance observer (PADO). As shown in eq.(9), $\tilde{T}_3^{dis}$ is calculated from $\dot{\boldsymbol{\theta}}$ and nominal matrix $\boldsymbol{M_3}$. Fig. 3 shows whole block diagram of PADO.

$$\begin{aligned} \hat{T}_3^{dis} &= \frac{g_{dis}}{s+g_{dis}}\{(\boldsymbol{M}_3 - \boldsymbol{M}_{mm3}\ddot{\boldsymbol{\theta}} + \acute{T}_3^{dis}\} \\ &= \frac{g_{dis}}{s+g_{dis}}(-M_{mmw}(\ddot\theta_r + \ddot\theta_l) - M_{mm33}\ddot\theta) \\ &= \frac{g_{dis}}{s+g_{dis}}(0 + g_{dis}\boldsymbol{M}_{mm3}\dot{\boldsymbol{\theta}}) - g_{dis}\boldsymbol{M}_{mm3}\dot{\boldsymbol{\theta}} \end{aligned} \qquad (9)$$

As mentioned before, PADO estimates total disturbance torque $\tilde{T}_3^{dis}$ including the modeling error of the pitch angle motion. To compensate the disturbance, the estimated value of $\tilde{T}_3^{dis}$ is fed back. To improve the stability and the robustness of wheelchair motion, disturbance observer (DOB) is also employed in right/left in-wheel-motors to compensate the disturbances imposed on each axle.

C. Stabilization Control Based on Lyapunov's Stability Theorem

To determine the torque input of each wheel, a candidate of Lyapunov function V shown in eq.(11) is considered.

$$V = \frac{1}{2}K_{\theta 1}(\theta - \theta^{cmd})^2 + \frac{1}{2}K_{\theta 2}(\dot\theta - \dot\theta^{cmd})^2 \qquad (10)$$

From eq.(10), $\dot V$ is calculated as follows.

$$\begin{aligned}\dot{V} &= K_{\theta1}(\theta-\theta^{cmd})(\dot{\theta}-\dot{\theta}^{cmd})+K_{\theta2}(\dot{\theta}-\dot{\theta}^{cmd})(\ddot{\theta}-\ddot{\theta}^{cmd}) \\ &= (\dot{\theta}-\dot{\theta}^{cmd})(K_{\theta2}\ddot{\theta}+K_{\theta1}(\theta-\theta^{cmd})-K_{\theta2}\ddot{\theta}^{cmd})\end{aligned} \tag{11}$$

Substituting eq.(8) to eq.(11), eq.(11) is rewritten as follows.

$$\begin{aligned}\dot{V} = (\dot{\theta}-\dot{\theta}^{cmd})[-&\frac{K_{\theta2}}{M_{mm33}}\{M_{mmw}(\ddot{\theta}_r+\ddot{\theta}_l)+\tilde{T}_3^{dis}\} \\ &+K_{\theta1}(\theta-\theta^{cmd})-K_{\theta2}\ddot{\theta}^{cmd})]\end{aligned} \tag{12}$$

Here $\tilde{T}_3^{dis}$ is estimated by PADO. Finally, the control input $(\ddot{\theta}_r^{ref}+\ddot{\theta}_l^{ref})$ is determined as follows so that $\dot{V}$ given in eq.(12) becomes semi-negative.

$$\ddot{\theta}_r^{ref}+\ddot{\theta}_l^{ref} = -\frac{1}{M_{mmw}}(M_{mm33}\ddot{\theta}^{ref}+\hat{T}_3^{dis}) \tag{13}$$

$$\ddot{\theta}^{ref} = \frac{K_{\theta1}}{K_{\theta2}}(\theta^{cmd}-\theta)+K_{\theta3}(\dot{\theta}^{cmd}-\dot{\theta})+\ddot{\theta}^{cmd} \tag{14}$$

If $\hat{T}_3^{dis}$ coincides with $\tilde{T}_3^{dis}$, eq.(12) is rewritten in eq.(15) using eq.(13) and eq.(14).

$$\dot{V} = -K_{\theta3}(\dot{\theta}-\dot{\theta}^{cmd})^2 \tag{15}$$

Equation (15) shows that $\dot{V}$ is semi-negative and the convergence of $\theta \to \theta^{cmd}$ and $\dot{\theta} \to \dot{\theta}^{cmd}$ are guaranteed according to LaSalle's theorem.

D. Whole Control System

When the disturbance of pitch angle direction is estimated by PADO perfectly, the transfer function from pitch angle command to pitch angle response is represented as eq.(16).

$$\frac{\theta^{res}}{\theta^{cmd}} = \frac{s^2+K_{\theta3}s+\frac{K_{\theta1}}{K_{\theta2}}}{s^2+K_{\theta3}s+\frac{K_{\theta1}}{K_{\theta2}}} \tag{16}$$

Equation (16) shows that continuous-path tracking control system is realized by the proposed approach. This makes it easy to determine the controller gains($K_{\theta1}$, $K_{\theta2}$, $K_{\theta3}$). The whole block diagram of the proposed controller is illustrated in Fig. 4.

IV. Simulation

This section shows simulation results to confirm the robustness of PADO&DOB based control system.

A. Simulation Setup

System parameters used in the simulation are shown in Table II. Ccontroller gains are summarized in Table III. Also, in the simulation, it is assumed that disturbancees of each system is given in eq.(17)∼eq.(19).

- Pitch angle direction

$$T_3^{dis} = \begin{cases} -12.0\sin(2\pi/6.0(t-2.0)) & (2.0 \le t < 5.0) \\ 12.0\sin(2\pi/6.0(t-18.0)) & (18.0 \le t < 21.0) \end{cases} \tag{17}$$

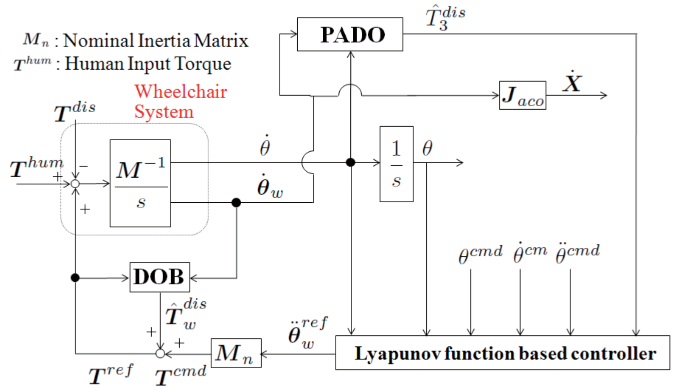


Fig. 4. The whole block diagram.

TABLE II
Parameters for simulation

parameter	value	parameter	value
R	0.26	m	35.0
M	78.0	l	1.0
W	0.7	K_t	2.1
J	2.0	J_w	0.6

- Right/left axle direction

$$T_r^{dis} = \begin{cases} 5.0\sin(2\pi/3.0(t-6.0)) & (6.0 \le t < 9.0) \\ 2.0 & (12.0 \le t < 14.0) \\ -2.0 & (15.0 \le t \le 17.0) \end{cases} \tag{18}$$

$$T_l^{dis} = \begin{cases} 5.0\sin(2\pi/3.0(t-6.0)) & (6.0 \le t < 9.0) \\ 2.0 & (12.0 \le t < 14.0) \\ -2.0 & (15.0 \le t \le 17.0) \end{cases} \tag{19}$$

Here the disturbance of pitch angle direction is regarded as human torque input induced by the rider's center of gravity (COG) movement. The disturbance of right/left axle corresponds to the influence of ground condition and so on. In the practical implemantation, it is difficult to know the real value of model parameters M and l described by inverted pendulum model. To confirm the robustness against these parameter uncertainties in the controller based on PADO, simulation is conducted about four cases summarized in Table IV.

B. Simulation Result

Fig.5 (a) shows pitch angle responses in case 1 and case 3. Fig.5 (b) shows estimated disturbance torque by PADO in case 3. Fig.5 (c) shows pitch angle responses in case 2 and case 4. Fig.5 (d) shows estimated disturbance torque by PADO in case 4. In the painted time period, the disturbances of pitch angle direction, right and left axle directions are imposed.

From Fig.5 (a) and Fig.5 (c), stable attitude response is obtained in all cases. It is found that case 3 and case 4 become more stable than case 1 and case 2 by PADO feedback. From Fig.5 (b) and Fig.5 (d), it seems that the disturbance estimation by PADO is not enough because of

TABLE III

GAIN PARAMETERS FOR SIMULATION

parameter	value	explanation
g_{disw}	14.0	cutoff freequency of DOB
g_{disp}	49.0	cutoff freequency of PADO
$\frac{K_{\theta 1}}{K_{\theta 2}}$	49.0	proportional gain
$K_{\theta 3}$	14.0	derivative gain

TABLE IV

CONDITION OF SIMULATION

case	with or without PADO feedback	Setting value of M	Setting value of l
case 1	without	68.0	0.8
case 2	without	88.0	1.2
case 3	with	68.0	0.8
case 4	with	88.0	1.2

the effect of right and left axle disturbances. In the proposed control system, however, the right and left axle disturbances are compensated by the disturbance observer (DOB) and the whole stability is not affected. As a result, it is confirmed that stable attitude response is realized by both PADO and DOB.

V. EXPERIMENTS

In this section, experimental results are shown to verify the practical validity of two wheels driven wheelchair based on PADO&DOB control system.

A. Experimental System

As described before, two in-wheel-motors are mounted on right and left sides of main body. The pitch angle and angular velocity of wheelchair are detected by gyro sensor. RT-Linux is used so that the constant sampling period 1msec is realized.

B. Experimental Setup

System Parameters used in experiment are shown in Table V. Controller gain for experiment are summarized in Table

TABLE V

PARAMETERS FOR EXPERIMENT

parameter	value	parameter	value
R	0.26	m	35.0
M	78.0	l	1.0
W	0.7	K_t	2.1
J	2.0	J_w	0.6

TABLE VI

GAIN PARAMETERS FOR EXPERIMENT

parameter	value	explanation
g_{disw}	14.0	cutoff frequency of DOB
g_{disp}	49.0	cutoff frequency of PADO
$\frac{K_{\theta 1}}{K_{\theta 2}}$	49.0	proportional gain
$K_{\theta 3}$	14.0	derivative gain

VI. Here the following two experiments are conducted.

- **Experiment I:** The rider sits on and gets off the two wheels driven wheelchair.
- **Experiment II:** The wheelchair goes over 2.5cm step for either the rider and the caregiver

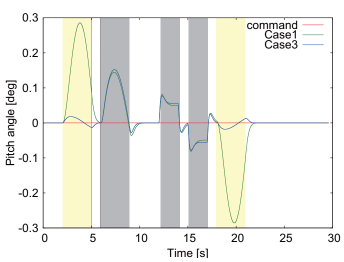
C. Experiment I

In the experiment I, the following two cases are compared.

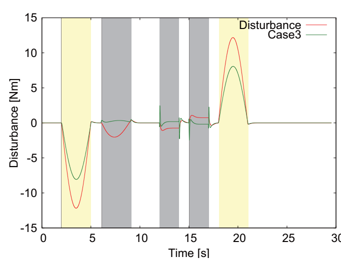
- **case 1:** without PADO
- **case 2:** with PADO

Fig.6 (a) shows pitch angle response in case 1. Fig.6 (b) shows estimated disturbance torque by PADO. Fig.7 (a) shows pitch angle response in case 2. Fig.7 (b) shows the estimated disturbance torque by PADO in case 2. The first painted time period shows that the riders sits on the wheelchair. The second one shows that the rider gets off the wheelchair. The third one shows that the wheelchair is fallen down by switching off the controller.

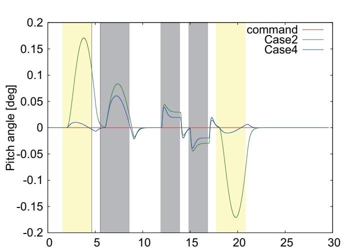
From Fig. 6 (a) and Fig. (b), stable attitude response is realized before the rider gets off. However, the wheelchair



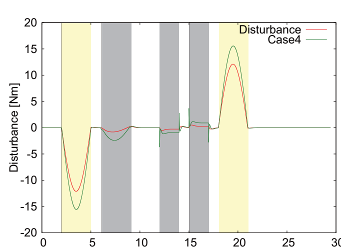
(a) Pitch angle response (case 1, case 3)



(b) Estimated disturbance torque by PADO (case 3)

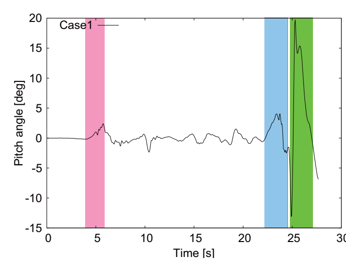


(c) Pitch angle response (case 2, case 4)

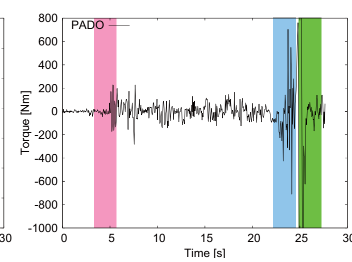


(d) Estimated disturbance torque by PADO (case 4)

Fig. 5. Simulation results.

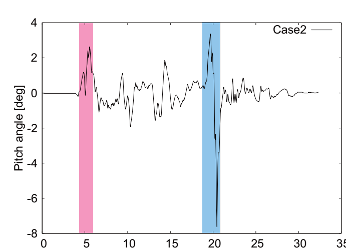


(a) Pitch angle response.

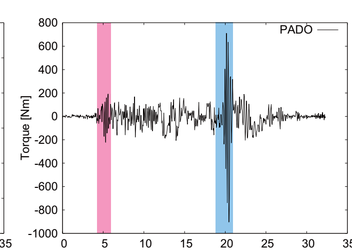


(b) Estimated torque by PADO.

Fig. 6. Experimental result of case 1.

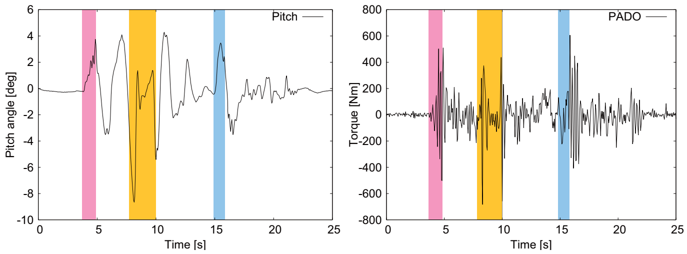


(a) Pitch angle response.



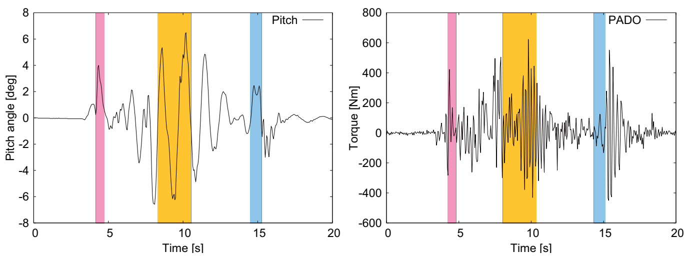
(b) Estimated torque by PADO.

Fig. 7. Experimental result of case 2.



(a) Pitch angle response. (b) Estimated disturbance torque by PADO.

Fig. 8. Step passage by rider.



(a) Pitch angle response. (b) Estimated disturbance torque by PADO.

Fig. 9. Step passage by caregiver.

motion becomes unstable after the rider gets off in case 1, that is, without PADO feedback. On the other hand, stable attitude response is achieved in all time periods in case 2, that is, with PADO feedback. From Fig. 6 (b) and Fig. 7 (b), large variation of the estimated disturbance torque is observed in pitch angle direction. This is caused by mass variation and inclination of two wheels driven wheelchair. This effect is compensated by PADO feedback and the stable attitude response is well realized in case 2.

D. Experiment II

In the experiment II, the following two cases of step passage motion by two wheels driven wheelchair are conducted.

- **case 1:** 2.5cm step passage by the rider's COG movement
- **case 2:** 2.5cm step passage by the caregiver

Fig.8 (a) shows pitch angle response in case 1. Fig.8 (b) shows estimated disturbance torque by PADO in case 1. Fig.9 (a) shows pitch angle response in case 2. Fig.9 (b) shows estimated disturbance torque by PADO in case 2. The first painted time period shows that the rider sits on the wheelchair. The second one shows that the wheelchair goes over the step. The third one shows that the rider gets off the wheelchair.

From Fig. 8 (a) and Fig. 9 (a), step passage is achieved without deteriorating the stable attitude response in both cases. From Fig. 8 (b) and Fig. 9 (b), large variation of the estimated disturbance torque by PADO is observed in each time period. However the stable attitude response is not affected. These results show that two wheels driven wheelchair is effective vehicle for not only riders but also caregivers support. Caregivers must add large torque in both horizontal and vertical directions for the step passage motion in the conventional wheelchairs. On the other hand, step passage motion is easily realized by small applied force of caregivers in the proposed wheelchair system. This is one of remarkable results of the proposed approach.

VI. CONCLUSIONS

A novel realization of two wheels driven wheelchair is proposed in this paper. The proposed wheelchair is higher mobility than the conventional ones. PADO based control well compensates disturbance of pitch angle direction and this brings sophisticated functions to the wheelchair. One of the important functions is a step passage. The validity of the proposed method is confirmed by simulation and experiment.

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