Development of Power-Assisted Wheelchair with Consideration of Driving Environment—Dynamic Estimation of Slope Angle and Adaptive Control System Design

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***Abstract*—The purpose of the present paper is to realize a high functionality of a power-assisted wheelchair with consideration of the driving environment. It is very important to recognize the environment in order to support wheelchair users and caregivers. In this paper, sensors are used to measure the state of the environment where is slope angle of uphill. Since these sensors implement to the wheelchair, the driving acceleration of wheelchair might influence the observed slope angle of the environment. This paper deals with the estimation problem of slope angle with acceleration compensation based on low-cost sensors. And this report also describes the adaptive control system design that is combined the estimation method of the slope angle. The effectiveness of the proposed estimation method and the adaptive control design is confirmed by simulation and experimental results. Finally, the proposed power-assisted wheelchair is evaluated by the biological signal such as an electromyography (EMG).**

***Index Terms*—power-assisted wheelchair, dynamic estimation, inclination sensor, adaptive control system, low-cost sensor, EMG, RMS**

I. Introduction

According to "The 2013 White Paper on an Aging Society" [1] published by the cabinet office, the total population of Japan is 127.52 million. The aged population comprised of persons 65 years over is 30.79 million which is the largest number ever. The ratio of the aging population (65 years over) was 24.1% in 2012, but will increase to 39.9% in 2060, showing that Japan has become a super-aged society in 2007. The ageing of the population raises the risks of a decline in the working population (shortage of caregivers) and an increase in pressure on government finances due to pension payments and medical expenses. In a super-aged society, it is very important to take advantage of engineering support for elderly assist. As one of engineering support and mobility support, power-assisted wheelchair which assists driving torque using actuators (electric motors) and spread their areas of life has been enhanced. The power-assisted wheelchair combines human torque which is delivered by the arms through the push-rims with output torque of electric motors. However, the power-assisted wheelchair increases the driving torque, responding to the environments (up-hill). Therefore, the excessive driving torque often causes a dangerous behavior of wheelchair. Moreover, the muscular power of the wheelchair user is decreased by the excessive assisting torque.

The purpose of this paper is to realize a high functionality of a power-assisted wheelchair with consideration of the driving environment. Some researchers [2] [3] have proposed the control system design method using the disturbance observer. However, the disturbance observer would be estimated as the disturbance terms including the modeling error, rolling friction and gravity term. The control performance of the disturbance observer becomes to be oscillatory generally. Therefore, the vibration of wheelchair feels the fear to the user.

In this paper, two inclination sensors are used to measure the state of the driving environment where is slope angle of uphill or downhill. Since inertia sensors implement to the wheelchair, the driving acceleration of wheelchair might influence the observed slope angle of the environment in general. Thus, this paper deals with the estimation problem of slope angle with acceleration compensation based on two inclination sensors. And this report also describes the adaptive control system design [4] that is combined the estimation method of the slope angle. The proposed method can estimate physical parameters that are total mass of user and wheelchair, coefficient of rolling friction and viscous coefficient. The effectiveness of the proposed estimation method and the adaptive control design is confirmed by simulation and experimental results. In this paper, an ideal power-assist system for the wheelchair is that the user can operate the wheelchair in the force-feeling like the level ground without influence of the driving environment. Therefore, the proposed power-assisted wheelchair is evaluated by the biological signal such as an electromyography (EMG).

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II. Description of Power-Assisted Wheelchair

In this chapter, we explain the dynamic model of wheelchair by driving torque of human on the driving environment that is the slope road of uphill or downhill. The dynamic model of the power-assisted wheelchair is extended by adding output torque of electric motor. Two motors that assist the user are equipped in each wheel.

A. Dynamic Model of Wheelchair

Fig. 1 shows the power-assisted wheelchair (Yamaha Motor Co. Ltd., JW-2) used in parameter identification and experiments. Motors that assist the user are equipped in each wheel. For the motion equations for the wheelchair as shown in Fig. 2, a mechanical model [5] has been used which gave the following equation:

$$f = M\ddot{x} + K\dot{x} + Mg(\mu\cos\theta + \sin\theta) \qquad (1)$$

where x is the displacement of moving direction, M, K and μ denote total mass of user and wheelchair, the coefficient of viscosity and coefficient of rolling friction, respectively. θ is the slope angle. g denotes the gravity acceleration. The input force f is given to the push rim by wheelchair user.

Figure 1. Power-assisted wheelchair (JW-2)

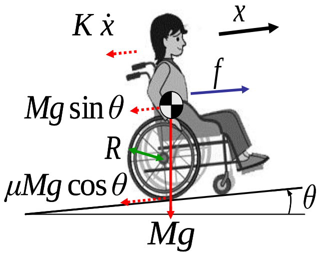


Figure 2. Dynamic model of wheelchair

B. Dynamic Model of Power-Assisted Wheelchair

The power-assisted wheelchair combines human torque τ_H which is delivered by the arms through the push-rims with output torque τ_M of electric motors. The human torque of each push-rim is measured by the toque sensor which is equipped on wheel device. Therefore, the dynamic model of the power-assisted wheelchair extends the wheelchair model eq. (1), by means of adding output torque of electric motor as following equation:

$$\tau = \tau_H + \tau_M = MR\ddot{x} + KR\dot{x} + MRg(\mu\cos\theta + \sin\theta) \qquad (2)$$

where R is the radius of rear wheel.

In order to realize a high functionality of the power-assisted wheelchair, it is necessary to estimate the state of the driving environment that is slope angle θ of uphill or downhill. Thus, we describe the dynamic estimation method of slop angle in next chapter.

III. Dynamic Estimation Method of Slope Angle

Many researchers [6] [7] have used the Kalman filter or the nonlinear observer to estimate the attitude of the rigid body with various kind of sensors for the acceleration motion. However, the modeling of noise characteristics and the turning of Kalman filter parameters are difficult. Thus, this paper deals with the estimation problem of slope angle (one of attitude) with acceleration compensation based on inclination sensor. We will describe the dynamic estimation method using two inclination sensors in this chapter.

A. Inclination Sensor Model

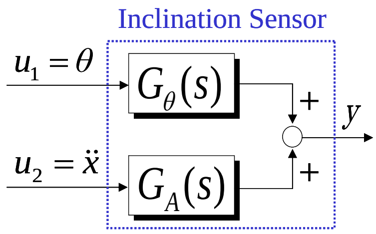


Figure 3. Inclination sensor model

In this paper, the inclination sensor model is applied as a two-input single-output system. Suppose that the inclination sensor model is the linear system. Fig. 3 shows the block diagram of the inclination sensor model. Thus, the dynamic model of inclination sensor gives as the following equation:

$$y = G_\theta(s)u_1 + G_A(s)u_2 \qquad (3)$$

where $u_1=\theta$ and $u_2=\ddot{x}$ are two input signals of the slope angle and the translational acceleration, respectively. y is the output signal of the inclination sensor. $G_\theta(s)$ denotes the transfer function between the output and input of slope angle. $G_A(s)$ denotes the transfer function between the output and input of translational acceleration. Since these transfer functions are unknown in general, we identify the unknown system based on the system identification [8].

B. System Identification for Inclination Sensor

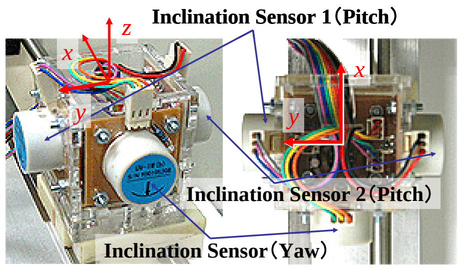


Figure 4. Inclination sensor box

In this section, we explain the identification method of $G_\theta(s)$ and $G_A(s)$, using the real inclination sensor(Midori America Co. Ltd., UV-1W) as shown in Fig. 4, The transfer function $G_\theta(s)$ is identified by the data of rotary motion. The transfer function $G_A(s)$ is identified by the data of translational motion (Slope Angle: u_1=0). The main conditions of identification experiment are shown as follows:

・Sampling Period : 0.01 [s]
・Sampling Number : 4096
・Input Data: Pseudo Random Binary Signal (Maximum Length)
・Model: ARX-Model (Auto-Regression with eXtra Inputs Model)
・Criterion of Fit: AIC (Akaike's Information Criterion)

The Akaike's Information Criterion is a way of selecting a model (order and structure) from a set of models.

C. Identification of Gθ(s): Rotary Motion

We need the transfer function $G_\theta(s)$ for how output signal y depends on input signal u_1. Thus, in order to identify the function $G_\theta(s)$, we made the experimental device (See Fig. 5) which is driven by DC motor for the rotary motion (Translational Acceleration: u_2=0).

We measure:

・Input u_1: Rotary encoder data
・Output y : Inclination sensor data

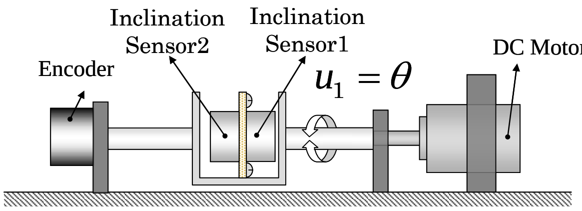


Figure 5. Experimental Device for Rotary Motion

As the results of system identification, $G_\theta(s)$ was obtained as the first order transfer function:

$$G_\theta(s) = \frac{y}{u_1} = \frac{13.2}{s+13.2}$$

The bandwidth 13 rad/s is the same value as response frequency 2 Hz of the sensor specification. Since order of AIC-model is generally high, the obtained model is the low-dimensional model (Reduced-order modeling by dominant eigenvalue technique) using the AIC-Model.

D. Identification of $G_A(s)$: Translational Motion

We need the transfer function $G_A(s)$ for how output signal y depends on input signal u_2. Thus, in order to identify the function $G_A(s)$, we made the experimental device (See Fig. 6) which used the ball screw driving mechanism for the translational motion (Slope Angle: u_1=0).

We measure:

・Input u_2: Rotary encoder data
・Output y : Inclination sensor data

As the results of system identification, $G_A(s)$ was obtained as the second order transfer function:

$$G_A(s) = \frac{y}{u_2} = \frac{1980}{s^2 + 34.7\,s + 926}$$

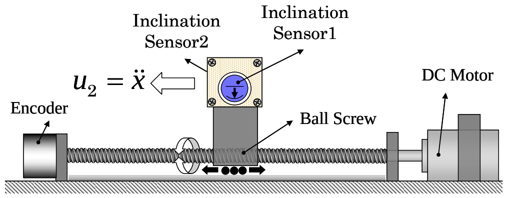


Figure 6. Experimental device for translational motion

E. Dynamic Estimation Method

We consider the dynamic estimation method of slope angle and acceleration information, using two inclination sensors of the same type. The dynamic models of two sensors can be rewritten as the following equations:

$$y_1 = G_{\theta 1}(s)u_1 + G_{A1}(s)u_2 \text{ : Inclination Sensor 1} \quad (4.1)$$

$$y_2 = G_{\theta 2}(s)u_1 + G_{A2}(s)u_2 \text{ : Inclination Sensor 2} \quad (4.2)$$

If the acceleration input u_2 with high accuracy is obtained by eq.(6) (Inclination Sensor 2), the estimated value of the slope angle $\theta_E = u_1$ can be easily calculated by eq.(5):

$$\theta_E = u_1 = G_{\theta 1}^{-1}(s)F_\theta(s)[y_1 - G_{A1}(s)u_2] \quad (5)$$

If the slope-angle input u_1 with high accuracy is obtained by eq.(5) (Inclination Sensor 1), the estimated value of the translational acceleration $\ddot{x}_E = u_2$ can be easily calculated by eq.(6):

$$\ddot{x}_E = u_2 = G_{A2}^{-1}(s)F_A(s)[y_2 - G_{\theta 2}(s)u_1] \quad (6)$$

where $F_\theta(s)$ and $F_A(s)$ are appropriate low-pass filters.

TABLE I. PHYSICAL PARAMETERS

Parameters	Values [unit]
M	90 [kg]
K	120 [Ns/m]
μ	0.01 [-]
R	0.3 [m]
θ	4 [deg.]

The proposed method compensates the dynamic characteristics such as the slope angle and the translational acceleration. Fig. 7 shows the block diagram of the proposed method. Values of physical parameters used in the simulation are shown in Table 1.The sampling period is 0.01 s. The simulation time is 15 s and the slope (Slope Angle: θ = 4.0 deg.) of the environment starts at 5 s. Fig. 8 shows the simulation results of the dynamic estimation method. From Fig. 6, the effectiveness and of the proposed estimation method (Eqs. (5) and (6)) was confirmed by the simulation in the Matlab/Simulink. For the numerical simulation, we used the values shown in Table I. These parameters represent the physical parameters of the wheelchair and the driving environment.

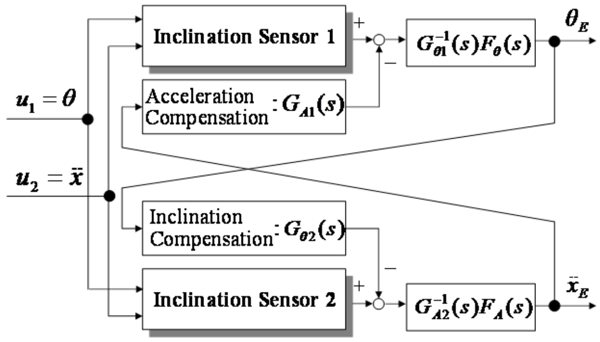
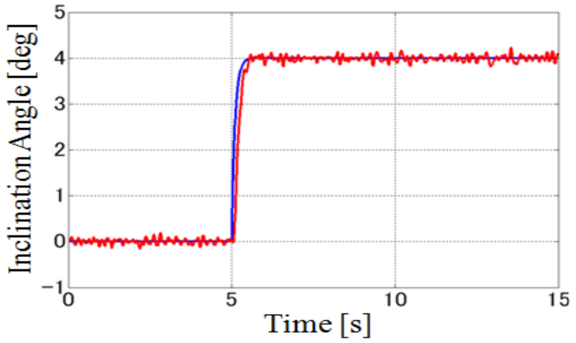
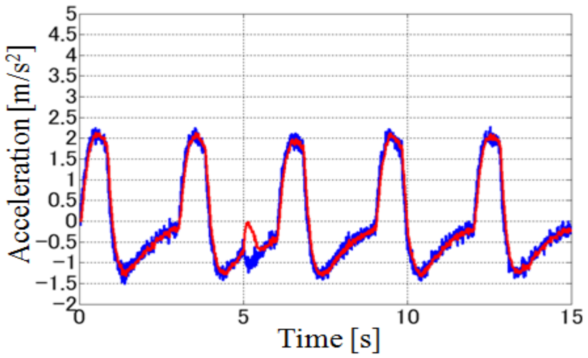


Figure 7. Proposed estimation method



(a) Estimationed inclination angle



(b) Estimationed acceleration

Figure 8. Simulation results of dynamic estimation method

IV. Control System Design

Control system design will be discussed in this chapter for task such as the adaptive-control system design consisting of the control law and the estimation law.

A. *Adaptive Control System Design*

In order to extend the foregoing estimation to the unknown parameter case, we use the linear in the parameters property of wheelchair dynamics. Now, consider eq. (1) in closed loop with:

$$\tau = \hat{M}R\ddot{x}_d + \hat{K}R\dot{x}_d + \hat{\mu}_M Rg\cos\theta_E + \hat{M}Rg\sin\theta_E - K_D\dot{e} - K_P e \quad (7.1)$$

$$= \boldsymbol{Y}(\ddot{x}_d, \dot{x}_d, \theta_E)\hat{\boldsymbol{\varphi}} - K_D\dot{e} - K_P e \quad (7.2)$$

$$\because e = x - x_d \text{ : Control error}$$

$$\boldsymbol{Y}(\ddot{x}_d, \dot{x}_d, \theta_E) = [R(\ddot{x}_d + g\sin\theta_E) \quad R\dot{x}_d \quad Rg\cos\theta_E]^T$$

: Regressor matrix

where ^ denotes the estimation value, θ_E is the estimated slope-angle, x_d is the desired trajectory and $\hat{\boldsymbol{\varphi}} = [\hat{M} \quad \hat{K} \quad \hat{\mu}_M]^T$ represents a vector of unknown parameters ($\because \mu_M = \mu \cdot M$).

And a vector of unknown parameter $\hat{\varphi}$ adjusted by

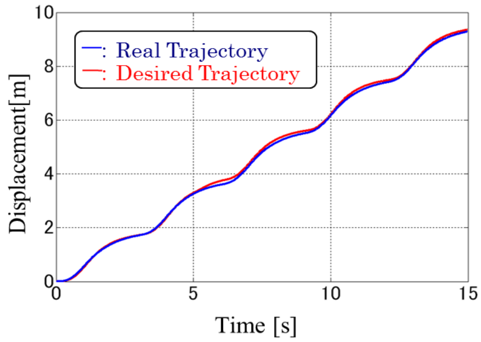
$$\dot{\hat{\boldsymbol{\varphi}}} = -\boldsymbol{\Gamma}\boldsymbol{Y}^T S \qquad \because S = \dot{e} + \lambda e \quad (8)$$

where λ is a positive parameter.

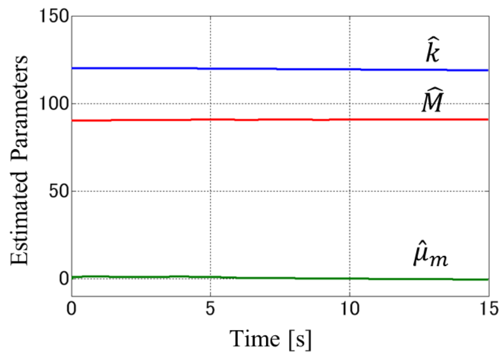
By the Lyapunov's theorem, the control error e and $\dot{e}$ converge to *0* as time tends to infinity. Thus, we have proved the validity of the adaptive control design consisting of the control law (eq. (7)) and estimation law (eq. (8)).

B. *Simulation Results*

The simulation of the adaptive control was performed on the Matlab/Simulink. Values of physical parameters are same values of the simulation as Table I of Chapter 3. The feedback gains of the servo compensation ware chosen to be K_P=100Nms, K_D=20Nm. Fig. 9, shows the results of the control performance and the physical parameters. From Fig. 9, the effectiveness of the proposed adaptive control design was confirmed by the simulation.



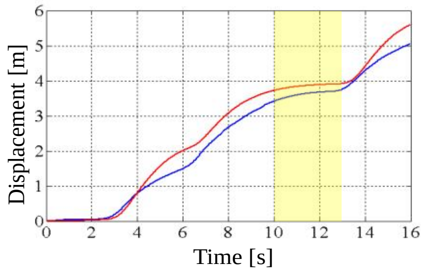
(a) Control performance



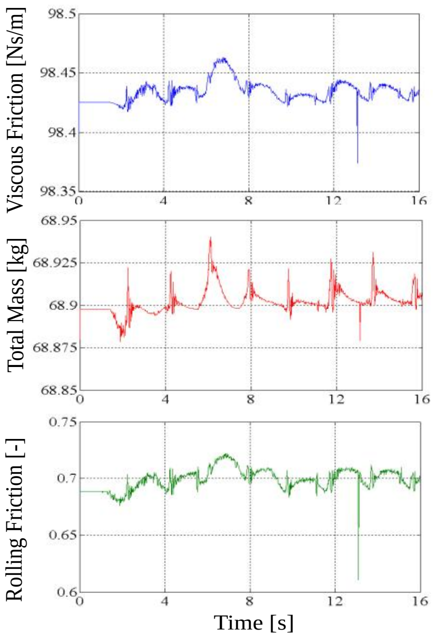
(b) Estimated physical parameters

Figure 9. Simulation results of the adaptive control

C. Experimental Results



(a) Control performance



(b) Estimated physical parameters

Figure 10. Experimental results of the adaptive control

Fig. 10(a), shows the experimental results of the control performance During the 13 s from about 10 s, the wheelchair user released the hand from the push-rim on the slope(Slope Angle: θ = 4.0 deg.). From Fig. 10(a), the user was able to ride the wheelchair with hands-free. And the wheelchair was stopped on the slope. Fig. 10(b) shows the estimation results of the physical parameters. Since the estimation law (eq. (8)) might influence the observed sensor noise, all estimated values are vibrating, but these values converge to substantially constant values. From the above results, the effectiveness of the adaptive control design was confirmed by the experimental results.

V. Evaluation of Power-Assisted Wheelchair

In this paper, an ideal power-assist system for the wheelchair is that the user can operate the wheelchair in the force-feeling like the level ground without influence of the driving environment. It is not that the user can operate the wheelchair by means of a small force. Therefore, the proposed power-assisted wheelchair is evaluated by the biological signal such as an electromyography (EMG).

A. Measurement System and Position

Upper-arm muscle activities are documented with three polar amplified surface electrodes (Wireless EMG Sensor (LP-WS1221) as shown in Fig. 11, Size:26.6×18.4×7.4mm, Mass:20g , Logical Product Co.) with a single ground electrode, and are placed (See Fig. 12) on an adductor pollicis muscle, the triceps brachii muscle and biceps brachii muscle. The data of an adductor pollicis muscle, is used to determine exactly period which holds the hand rim of the wheelchair. These muscles are chosen for their role in elbow flexion and extension.

Figure 11. Wireless EMG sensor (LP-WS1221)

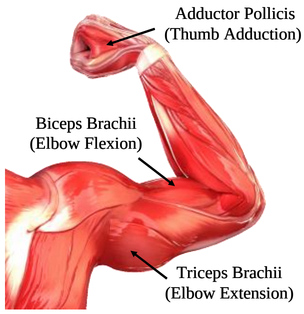


Figure 12. Measurement placement (Right Arm)

The skin surface is prepared by cleaning the area with an alcohol preparatory. After three EMG sensors are secured, EMG data are saved into the hard disk, which is connected to the computer via wireless sensors. The data are collected at the law voltage values with gain settings (amplified 500 times the input signal). The data are sampled on a computer at a rate of 100Hz.

B. Data Processing and Analysis

This study focused on data derived from the right upper limb during the propulsion (contact) phase of the push stroke only. Healthy participant was asked to propel their wheelchair at constant pace (about 0.5Hz) for 10s. EMG from five successive push strokes were collected; once data collection began, the initial one push strokes were neglected, and the next four consecutive push strokes were saved for analysis. Fig. 13 shows the integral EMG signals of two placements (an adductor pollicis muscle and the triceps brachii muscle).

From Fig. 13(a), when the participant grips the hand rim, integral EMG signal of an adductor pollicis muscle occur the peak value at the point A. After a participant releases the hand from the hand rim, integral EMG signal of the adductor muscle is 0 at the point B. The propulsion (contact) phase of the push stroke is the period between point A and point B. On the other hand, the triceps brachii muscle is active in the propulsion phase as shown in Fig. 13(b). Therefore, we discuss the propulsion phase only.

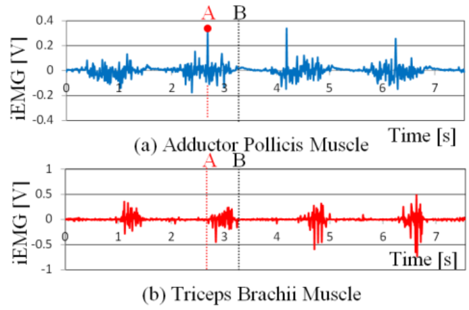


Figure 13. Measurement results of iEMG signal

RMS (Root Means Square) value is extracted by calculating the integral EMG from the raw EMG signals. The σ_{RMS} is determined as:

$$\sigma_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

where x_i is the intgral EMG signal of the triceps brachii muscle at i th sampling and N is the number of samples in a segment.

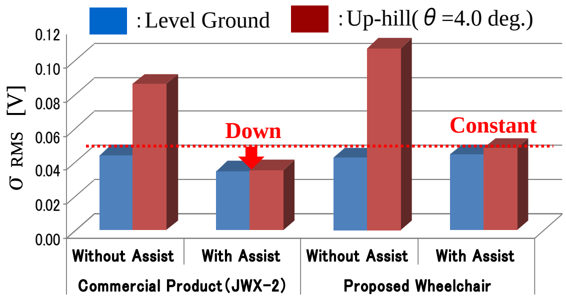


Figure 14. Comparison between commercial product and propoed wheelchair (RMS Values)

Fig. 14 shows results of the performance comparison between the commercial product (Yamaha Motor Co. Ltd., JWX-2: Latest Type) and the proposed wheelchair. Commercial product is caused excessive assist. In case of the proposed wheelchair, the participant can operate the wheelchair in the force-feeling like the level ground without influence of the driving environment (Up-hill).

VI. Conclusion

The purpose of the present paper is to realize a high functionality of a power-assisted wheelchair with consideration of the driving environment. In order to measure the state of the driving environment where is slope angle of uphill or downhill, we proposed the dynamic estimation method using the two inclination sensors of the same type. And this paper also proposed the adaptive control system design that was combined the estimation method of the slope angle. The proposed method could estimate physical parameters that are total mass of user and wheelchair, coefficient of rolling friction and viscous coefficient. The effectiveness and the validity of the proposed estimation method and the adaptive control design ware confirmed by simulation and experimental results. Finally, the effectiveness of the proposed wheelchair was confirmed by the biological signal such as an electromyography (EMG).

Acknowledgments

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