

Control System for a Power-Assisted Wheelchair on Sloping Terrain Using IMU

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Abstract

The demand for safe and user-friendly mobility support systems has increased with the aging population and the need to assist disabled people. Wheelchairs are one of the targets of such systems, with motorized functions that extend usability across diverse scenarios. This paper presents a control system for power-assisted wheelchairs operating in sloping terrain using an Inertial Measurement Unit (IMU) sensor. Unlike conventional methods that only consider straight uphill movement, the proposed approach compensates for disturbances encountered when the wheelchair moves along a slope diagonally.

Keywords

Power-assisted wheelchair, inertial measurement unit, disturbance compensation

1. Introduction

With the rapid growth of the elderly population, human-machine cooperative systems have become increasingly important in supporting older adults and individuals with physical disabilities (Pineau et al. 2003, Broadbent et al. 2009). A key application of these systems is the power-assisted wheelchair, which provides essential mobility support and promotes social participation. To make the motion of a power-assisted wheelchair easy, several control methods have been proposed. Kaida and Murakami (2006) proposed a method to control the assist to attach an in-wheel motor

to the wheel of a wheelchair without a force sensor and control the amount of assist by the amount of current flowing to the motor. Li and Zhu (2019) developed a retrofit electric drive unit to provide assistance without a force sensor. Recent advances in sensor technology have enabled more sophisticated environmental recognition, enhancing the safety and comfort of power-assisted wheelchairs. Oonishi et al. (2010) introduced a new control method that integrates an electromyogram (EMG) sensing with a disturbance observer to estimate human torque, achieving fast and stable assistance. Nakajima et al. (2023) devised an assist control that measures the angle of inclination from an inclination angle sensor and generates a torque generated by motors for assisting the human power. However, the control method in the paper of Nakajima et al. (2023) is limited to straight uphill movement since its model does not take into account the wheelchair rotation. To address this limitation, we extend the mathematical model and propose a new control method that enables a power-assisted wheelchair to move diagonally across a slope while maintaining a constant speed.

2. Problem Formulation

Consider a wheelchair moving diagonally on a slope with inclination angle $\alpha_s(t) (< \pi/2)$ [rad]. Let $\theta_s(t)$ [rad] denote the heading direction of the wheelchair relative to the slope's fall line and θ [rad] represent the tilt angle of the wheelchair relative to its trajectory. In this situation, from Seki et al. (2006) and Liang Ding et al. (2018), the equations of motion of the wheelchair are expressed as:

$$\frac{u_h(t) + u_m(t)}{r} = M\dot{v}(t) + kv(t) + u_{fg}(t) \quad (1)$$

and

$$I_v\ddot{\theta}(t) = \frac{u_h(t)}{r}l - D\dot{\theta}(t) - \frac{u_m(t)}{r}l + u_{mg}(t). \quad (2)$$

Here, $u_h(t)$ is the torque generated by the user's force, $u_m(t)$ is the assisted torque generated by the motor, r is the radius of the wheel, M is the total mass of the wheelchair and user, $v(t)$ is the velocity of the wheelchair, k is the axial viscosity coefficient of the wheel, I_v is the moment of inertia, l is the distance from the axle center to the wheels, D is the viscous resistance coefficient of when turning and g is the acceleration of gravity. $u_{fg}(t)$ and $u_{mg}(t)$ are the disturbance force and moment generated by gravity, written by:

$$u_{fg}(t) = Mg \sin \alpha_s(t) \sin(\theta_s(t) + \theta(t)) \quad (3)$$

and

$$u_{mg}(t) = (Mg \sin \alpha_s(t) \sin(\theta_s(t) + \theta(t)))l. \quad (4)$$

Using $u_{fg}(t)$ in (3) and $u_{mg}(t)$ in (4), $u_g(t)$ is given by:

$$u_g(t) = \begin{bmatrix} u_{fg}(t) \\ u_{mg}(t) \end{bmatrix}. \quad (5)$$

When the wheelchair moves diagonally on a slope, $u_g(t)$ in (5) has a negative effect on the input-output property from $u_h(t)$ to $v(t)$ and $\theta(t)$. Thus, the influence of $u_g(t)$ on $v(t)$ and $\theta(t)$ should be attenuated.

From (1) and (2), the transfer function from $u_h(s) = \mathcal{L}[u_h(t)]$, $u_m(s) = \mathcal{L}[u_m(t)]$ and $u_g(s) = \mathcal{L}[u_g(t)]$ to $[v(s) \ \theta(s)]^T$ is given by:

$$\begin{bmatrix} v(s) \\ \theta(s) \end{bmatrix} = G(s) \begin{bmatrix} \frac{u_h(s)}{r} \\ \frac{u_h(s)}{r}l \end{bmatrix} + G(s) \begin{bmatrix} \frac{u_m(s)}{r} \\ \frac{u_m(s)}{r}l \end{bmatrix} + G_d(s)u_g(s), \quad (6)$$

where $v(s) = \mathcal{L}[v(t)]$, $\theta(s) = \mathcal{L}[\theta(t)]$, $u_{fg}(s) = \mathcal{L}[u_{fg}(t)]$ and $u_{mg}(s) = \mathcal{L}[u_{mg}(t)]$,

$$G(s) = \text{diag} \left\{ \frac{1}{Ms + k}, -\frac{l}{s(I_v s + D)} \right\}, \quad (7)$$

and

$$G_d(s) = \text{diag} \left\{ -\frac{1}{Ms + k}, \frac{1}{s(I_v s + D)} \right\}. \quad (8)$$

The input from the motors, that is, the assisted torque $u_m(s)$, can be used to attenuate these disturbances. $u_m(s)$ is manipulated by changing the input voltages of the left and right motors. From Nakajima et al. (2023), $u_m(s)$ is given by:

$$u_m(s) = G_0(s) \begin{bmatrix} u_r(s) \\ u_l(s) \end{bmatrix}, \quad (9)$$

where $u_r(s)$ and $u_l(s)$ are the input voltages of the right and left motors, respectively. $G_0(s)$ is the function denoted by:

$$G_0(s) = \text{diag} \{G_{0r}(s), G_{0l}(s)\}, \quad (10)$$

where $G_{0r}(s)$ and $G_{0l}(s)$ are the transfer function from $u_r(s)$ and $u_l(s)$ to the assisted torque of motors. According to Nakajima et al. (2023), $G_{0r}(s)$ and $G_{0l}(s)$ have to satisfy:

$$G_{0r}(0) = G_{0l}(0) = \frac{k_t}{R}, \quad (11)$$

where $R \in \mathbf{R}$ is the resistance of the motor and $k_t \in \mathbf{R}$ is the torque constant. From (11), since $G_{0r}(s)$ and $G_{0l}(s)$ treat the transfer function of the motor as a constant gain, $G_{0r}(s)$ and $G_{0l}(s)$ in this paper are settled as:

$$G_{0r}(s) = G_{0l}(s) = \frac{k_t}{R}. \quad (12)$$

This paper examines a problem of designing a control method for the wheelchair that attenuates the influence of $u_g(t)$ in (5) by using values obtained from the IMU sensor.

3. Power-Assisted Control Using IMU Measurements

In this section, we propose a control method for the wheelchair that attenuates the influence of $u_g(t)$ in (5) on $v(t)$ and $\theta(t)$ by using the IMU sensor. Using the IMU sensor, $\alpha_s(t)$ and $\theta_s(t) + \theta(t)$ can be measured. Using $\alpha_s(t)$ and $\theta_s(t) + \theta(t)$, $u_g(t)$ in (5) can be calculated. Let the calculated $u_g(t)$ in (5) using measurement values of the IMU sensor denote $\bar{u}_g(t)$ as:

$$\bar{u}_g(t) = \begin{bmatrix} Mg \sin \alpha_s(t) \sin(\theta_s(t) + \theta(t)) \\ (Mg \sin \alpha_s(t) \sin(\theta_s(t) + \theta(t)))l \end{bmatrix}. \quad (13)$$

Here, it is assumed that:

$$\bar{u}_g(t) = u_g(t). \quad (14)$$

Using $\bar{u}_g(t)$ in (13), $u_r(s)$ and $u_l(s)$ in (9) is given as:

$$\begin{bmatrix} u_r(s) \\ u_l(s) \end{bmatrix} = -(G(s)LG_0(s))^{-1}q(s)G_d(s)\bar{u}_g(s), \quad (15)$$

where L is

$$L = \text{diag} \left\{ \frac{1}{r}, \frac{l}{r} \right\}, \quad (16)$$

$\bar{u}_g(s) = \mathcal{L}[\bar{u}_g(t)]$ and $q(s)$ is a filter denoted by:

$$q(s) = \text{diag} \left\{ \frac{1}{(1 + \tau_1 s)^{\alpha_1}}, \frac{1}{(1 + \tau_2 s)^{\alpha_2}} \right\}, \quad (17)$$

where $\tau_i \in \mathbf{R}$ ($i = 1, 2$) is any positive number and $\alpha_i \in \mathbf{R}$ is any positive integer that makes $(G(s)LG_0(s))^{-1}q(s)$ proper.

Using (15), the input from the motor $u_m(s)$ is rewritten as:

$$u_m(s) = G_0(s) \begin{bmatrix} u_r(s) \\ u_l(s) \end{bmatrix} = G_0(s) \left\{ -(G(s)LG_0(s))^{-1}q(s)G_d(s)\bar{u}_g(s) \right\}. \quad (18)$$

From (18) and the assumption that $\bar{u}_g(s)$ satisfies (14), the transfer function in (6) can be written as:

$$\begin{bmatrix} v(s) \\ \theta(s) \end{bmatrix} = G(s) \begin{bmatrix} \frac{u_h(s)}{r} \\ \frac{u_h(s)}{r}l \end{bmatrix} + (I - q(s))G_d(s)u_g(s). \quad (19)$$

From (19), on the frequency range ω satisfying $q(j\omega) \cong 1$, $v(s)$ and $\theta(s)$ satisfies:

$$\begin{bmatrix} v(j\omega) \\ \theta(j\omega) \end{bmatrix} \cong G(j\omega) \begin{bmatrix} \frac{u_h(j\omega)}{r} \\ \frac{u_h(j\omega)}{r}l \end{bmatrix}. \quad (20)$$

This implies that the motor inputs $u_m(s)$ attenuate the influence of $u_{fg}(s)$ and $u_{mg}(s)$ on $v(s)$ and $\theta(s)$, so that $v(s)$ and $\theta(s)$ depend only on the user input.

4. Conclusion

In this paper, we have extended the result of Nakajima et al. (2023) to obtain the new mathematical model of the power-assisted wheelchair and proposed a control method that enables the power-assisted wheelchair to travel diagonally across a slope while the user is in the wheelchair and go straight ahead at a constant speed.

Future work will focus on validating the proposed control strategy through both numerical simulations and experimental implementation on an actual power-assisted wheelchair platform. In addition, the proposed approach can be extended to more complex terrain conditions, such as time-varying slopes, uneven surfaces, and more realistic driving scenarios. These investigations will help further clarify the practical applicability and robustness of the proposed method.

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