Measurement 120 (2018) 175–181

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Experimental comparison of torque balance controllers for power-assisted wheelchair driving

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ARTICLE INFO

Keywords:
Power-assisted wheelchair
Torque balance control
Temporal difference

ABSTRACT

A power-assisted wheelchair amplifies the user's propulsion power. If the user's arm strength is unbalanced, this can affect the driving balance. In order to correct this imbalance, a method of producing an assisting torque by cross-referencing the opposite input torque was developed. One proposed torque balance control scheme involves automatically controlling the cross-reference proportion according to the amplitude ratio of the left and right input torques. However, this scheme cannot improve the driving performance under all conditions because instability is inherent to the user's propelling torque. To resolve this problem, a new torque balance control method is proposed that considers not only the proportion of input torques but also the temporal difference. This study examined the usefulness of the proposed torque balance control method based on the temporal difference through a comparison with the existing method via a driving simulation and experiment.

1. Introduction

A push-rim activated power assisted wheelchair (PAPAW) is a special wheelchair that detects the user's propulsion torque on the push-rim and assists the wheelchair's driving torque with a motor device to lessen the user's physical fatigue. Its operation is as simple as that of a manual wheelchair, but its motor assists with the driving torque. Thus, PAPAW can be helpful in rehabilitating the disabled. The potential risk factors of shoulder injury have been reported to be reduced, especially for users of passive wheelchairs [1]. This benefit is also useful for SCI patients [2].

The PAPAW research topic can be classified into two broad categories as follow: a method of detecting a user's force applied to a push-rim and a driving control method for improving the driving performance. The power and the signal must be connected to the torque sensor mounted on the rotating push-rim without twisting the wire so that the propulsive force of the user could be measured.

Non-contact torque recognition methods have been actively studied for the purpose of transmitting signals to a rotating wheel [3,4]. Especially, Yamaha Co. developed the first commercialize PAPAW and applied a circular connector that uses magnetic flux changes [3]. Alber Co. solved the wire twist problem by integrating the battery, control, and sensor device into a rotating wheel [5]. In recent years, some studies have actively been conducted on a torque sensor-less method of estimating the user propulsive torque by detecting the motion of a minute wheel caused by a user propelling a wheelchair without using direct torque sensors on a push-rim [6–8]. These methods were structurally simple because they do not require a special device for power and signal transmission. However, a problem in disturbance remains. Hence, much research is still needed.

The second research topic is about driving performance improvement. As we have mentioned earlier, PAPAW is driven by the user's arm propulsion. However, people's left and right arms often have different strength levels. Therefore, the direction frequently needs to be corrected on the side with lesser power to make the wheelchair go straight. However, in the case of a PAPAW, the user's driving propulsion torque is amplified by the motor power. Hence, unbalanced arm strengths have a stronger effect on the wheelchair's driving performance.

Torque balance control is generally used to improve the PAPAW driving performance. In the torque balance control, the assisting torque is determined by cross-referencing the opposite input torque to maintain a certain ratio [9,10]. Seki particularly suggested a torque balance control method, where the user's driving intention is recognized based on the proportion of the left and right input torques, and the cross-reference ratio is adjusted to improve both the straight and rotation driving performances.

However, detecting the driver's driving intentions by using only the proportion of torques has limitations because the user's left and right propulsion torques are uneven and have a temporal difference. In this study, we propose a new driving control method to solve this problem and better reflect the user's driving intention by additionally considering the temporal difference between two input torques [11].

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https://doi.org/10.1016/j.measurement.2018.02.024
Received 18 March 2016; Received in revised form 2 May 2017; Accepted 14 February 2018

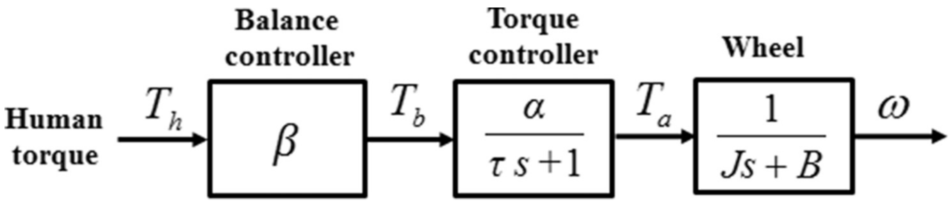

Fig. 1. PAPAW control system structure.

This study compares the existing torque balance control method and a new torque balance controller that considers the temporal difference between the left and right propulsion torques to detect the user's driving intention via a driving simulation and an experiment. The results show that considering the temporal difference improved the straight and rotation driving performances.

2. Torque balance controller

2.1. Overview

Fig. 1 shows the PAPAW control system. The balance controller generates the balance torque T_b to decrease the instability of the user input torque T_h. β represents the cross-reference ratio. The torque controller consists of a low-pass filter and generates the assisting torque T_a. The assistance ratio is denoted by α. The time constant τ switches from τ_{fast} to τ_{slow} when the user releases the push rim to generate virtual inertia [10,12]. The motorized wheel is modeled with the inertia moment J and viscosity B.

The PAPAW control system detects the user's propulsion torque on the left and right push rims and generates assistive torque with motors. Since the left and right sides of the system work independently, when the user's left and right arm strengths are unbalanced, the PAPAW may be difficult to move in a straight line. Hence, a controlling device is needed for stable driving to correct the unbalance torque of the user.

To correct the unbalanced propulsion torque of the user on the left and right wheels, one method involves referencing the torques of both sides at a certain ratio to generate a common torque that is applied to the outputs on both sides. Fig. 2 shows the cross-referencing method for generating assisting torques on both sides. Here, a and b are the reference ratios of the left and right torques, respectively, to generate the common cross-referenced torque. α and β are the amplification ratios of the left and right input torques used to generate the assisting torque.

However, this method has certain problems, such as a decreased rotation driving performance while improving the straight driving performance when the proportion of the common torque is too large. When the proportion of the common torque is too small, the straight driving performance is reduced. To resolve this problem, Seki proposed a torque balance method where the reference ratio is adjusted according to the proportion of the left and right torques to reflect the user's driving intention [10]. However, the torque ratio includes the instability due to the user's imbalance on the left and right sides, so it has limited ability to reflect the user's driving intention.

To address this problem, a torque balance control method was recently proposed that considers the temporal difference in addition to the proportion of the left and right input torques [11].

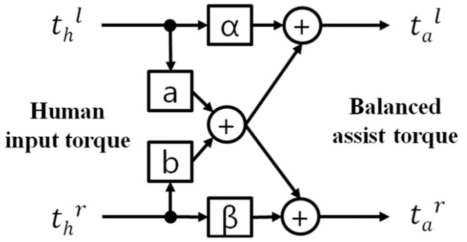

Fig. 2. Cross-referencing scheme for generating balanced assist torques.

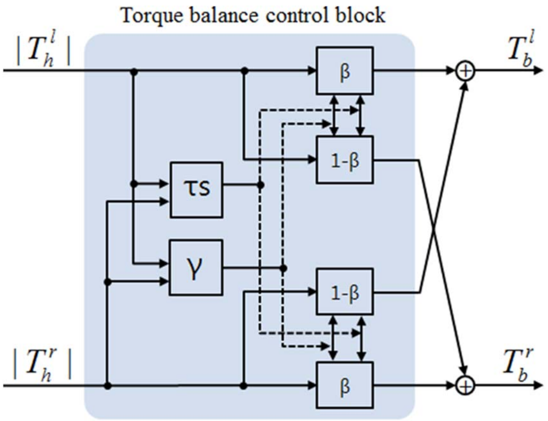

Fig. 3. Configuration block of the torque balance controller based on the torque proportion and temporal similarity.

2.2. Torque balance control based on torque and temporal differences

Fig. 3 shows the proposed torque balance controller that references not only the torque proportion, but also the temporal difference of the left and right side propelling torques. Symbol γ is the proportion of the user propelling torques with a range of −1 to 1 [10]. Symbol τs is the temporal similarity which weighted by the temporal difference between the left and right propulsive torques, and decreases as the temporal difference increases [Fig. 4(a)].

In the torque balance control block shown in Fig. 3, symbol β denotes the cross-referencing ratio for the left and right input torques that has been defined in the previous study as the balance ratio [10]. τs and γ are applied herein in combination for the optimal balance ratio selection. Eq. (1) represents the relationship between the user input torques (T_h^l, T_h^r) and the balance ratio (β) to generate balanced output torques (T_b^l, T_b^r). In addition, the sign of the output torque follows that of the input torque, but if the input torque does not occur, it follows the sign of the opposite side [11].

$$\begin{aligned} T_b^l &= \beta|T_h^l| + (1-\beta)|T_h^r| \\ T_b^r &= \beta|T_h^r| + (1-\beta)|T_h^l| \end{aligned} \tag{1}$$

Fig. 4(a) shows τs according to the temporal difference Δt and Fig. 4(b) shows the definition of the balance ratio (β) with the change of γ. The selection range of β proposed in this study can be varied in the range of the A to D section according to τs. By doing so, it becomes possible to choose more appropriate balance ratio which most closely matches the user's driving intent.

For example, the inflection points P1 and P2 move to the left near A and C when the intention is straight driving. This maximizes β, which references the input torque of the opposite side despite the large difference between the left and right torques. As a result, a stable balance torque can be generated. In contrast, the inflection points P1 and P2 move to the right near B and D when the intention is for a large rotation. Hence, β is minimized.

We performed herein a driving experiment, where the four changing section of β was set as follows: $A_\gamma = -0.8$, $B_\gamma = 0$, $C_\gamma = 0.5$, and $D_\gamma = 0.8$ on the transverse axis. The reference times, Δt_1 and Δt_2, were set to 200 ms and 400 ms, respectively.