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ADAPTIVE CONTROLLER FOR MOTION CONTROL OF SEAT-STYLE OMNIDIRECTIONAL MOBILE WALKER

Shuoyu Wang[1], Yuto Watanabe[1] and Renpeng Tan[2]

[1]School of Systems Engineering
[2]Research Organization for Regional Alliances
Kochi University of Technology
Tosayamada, Kami, Kochi 782-8502, Japan
{ wang.shuoyu; tan.renpeng }@kochi-tech.ac.jp; 1550047b@gs.kochi-tech.ac.jp

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Abstract. *Although the importance of rehabilitation is recognized across the spectrum of health and social care, how to realize early recovery is still a challenging subject. This paper reports the development of control method for a seat-style omnidirectional mobile walker (SOMW) to aid early recovery of patients who have not regained the power to stand. Training paths prescribed by physical therapists can be stored in the SOMW so that the patient can follow these reference paths during rehabilitation. However, path tracking errors occur due to load change and center of gravity shift when the patient is sitting on the SOMW. To address this problem, an adaptive control method is proposed herein. First, the kinematics and the kinetics of the SOMW are derived. An adaptive control strategy is then presented and the stability of the system is verified. Finally, an experiment is carried out to compare the performance of the control method with and without a load. The experimental results demonstrate the feasibility and effectiveness of the proposed method.*
Keywords: Seated training, Seat-style omnidirectional mobile walker, Load change, Center of gravity shift, Path tracking

1. **Introduction.** Walking is basic ability that is taken for granted in everyday life. However, in an aging society with a low birthrate, such as that in Japan, an increasing number of people need to undergo physical rehabilitation to regain the ability to walk following illnesses or accidents. Therefore, efficient training machines that can aid early recovery and reduce the burden on physical therapists and caregivers are strongly desired.

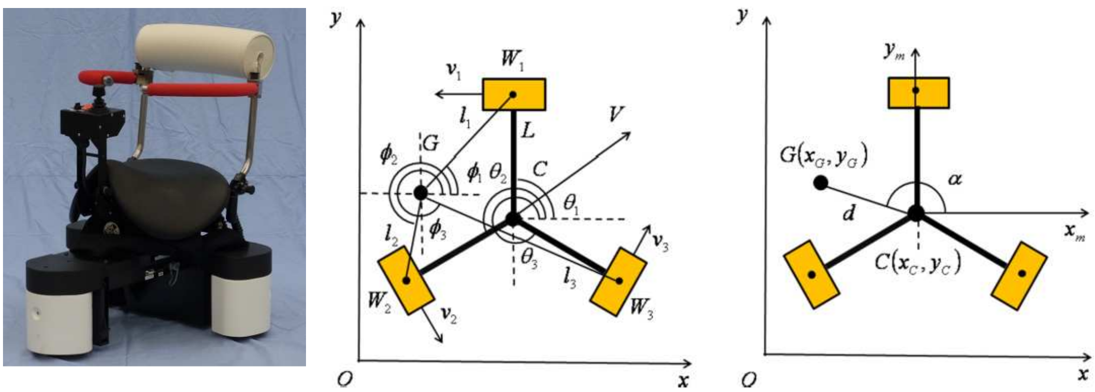
Walking rehabilitation mainly comprises three steps: in-bed exercises, standing exercises, and walking exercises. Bedridden patients are first trained to sit up in bed. Following this, a tilt table is used to perform exercises while standing up. Parallel bars or walkers are then used to perform walking exercises. In this way, patients can enhance the muscle strength in their lower limbs. At the present time, all walking training machines require the user to be able to stand up in order to carry out walking exercises. However, an earlier recovery might be possible if a training machine could help patients to perform walking exercises before they are fully capable of standing up.

The authors and their colleagues, for the first time in the world in 1999, proposed an omnidirectional walker which can provide safe walking rehabilitation. Studies from basic research to clinical trial have been carried out during the past decade [1-3]. A seat-style omnidirectional mobile walker (SOMW) was proposed for seated training in 2009 [4,5]. The SOMW can both provide aid in training the lower limbs and support indoor movement. In training mode, training paths prescribed by physical therapists can be stored in the SOMW. The patient sits on the SOMW and takes steps that follow its movement. In support mode, the SOMW can be used as a powered wheelchair. However, the SOMW can deviate from the prescribed path during training due to load change and center of gravity (COG) shift when the patient is sitting on the seat. To optimize the beneficial effects of training, the path tracking accuracy therefore needs to be improved. This paper focuses on improving the accuracy of path tracking under such load change and COG shift. The SOMW is a nonlinear system with variable system parameters. Therefore, it is difficult to deal with this problem using a conventional controller, such as a proportional-integral-derivative (PID) controller.

An adaptive control strategy, inspired by Slotine and Li [6], is proposed in this paper to deal with the load change and COG shift of the SOMW. This paper is organized as follows. Section 2 describes the structure, kinematics, and kinetics of the SOMW. Section 3 presents an adaptive control strategy to compensate for load change and COG shift caused by patients during rehabilitation. Section 4 describes an experiment to evaluate the effectiveness of the proposed method. A brief conclusion is given in Section 5.

2. **Seat-Style Omnidirectional Mobile Walker.** In this section, the structure of the SOMW is introduced, and the model considering the load change and COG shift is abstracted from the structure. The kinematics and kinetics of the SOMW are derived.

2.1. **Model.** A photograph of the SOMW is shown in Figure 1(a). It can achieve omnidirectional movement using three omniwheels at the bottom of its body, and this allows training of different muscles in the lower limbs. The coordinate system and the structural model are shown in Figure 1(b).



(a) Photograph of SOMW (b) Coordinate system and structural model

FIGURE 1. Seat-style omnidirectional mobile walker

The parameters and coordinates used to describe the SOMW are as follows:

$\sum(x, y, O)$: Absolute coordinate system
$\sum(x_m, y_m, C)$: Translated coordinate system of $\sum(x, y, O)$
$C(x_C, y_C)$: Geometric center of SOMW
$G(x_G, y_G)$: COG of SOMW
W_i: Position of each omniwheel
V: Velocity of SOMW
v_i: Velocity of each omniwheel
θ_i: Angle between x-axis and CW_i
ϕ_i: Angle between x-axis and GW_i
α: Angle between x-axis and GC
L: Distance between C and W_i
l_i: Distance between G and W_i
d: Distance between C and G
i: Index of omniwheel $(= 1, 2, 3)$

To develop a controller, kinematics and kinetics equations are derived based on the model to take into account load change and COG shift.

2.2. **Kinematics.** Based on the model shown in Figure 1(b), the kinematic equations in terms of G and C can be respectively written as:

$$\begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}^T = K_G \begin{bmatrix} \dot{x}_G & \dot{y}_G & \dot{\phi}_1 \end{bmatrix}^T \tag{1}$$

$$\begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}^T = K_C \begin{bmatrix} \dot{x}_C & \dot{y}_C & \dot{\theta}_1 \end{bmatrix}^T \tag{2}$$

where

$$K_G = \begin{bmatrix} -\sin\theta_1 & \cos\theta_1 & l_1\cos(\theta_1-\phi_1) \\ -\sin\theta_2 & \cos\theta_2 & l_2\cos(\theta_2-\phi_2) \\ -\sin\theta_3 & \cos\theta_3 & l_3\cos(\theta_3-\phi_3) \end{bmatrix}, \quad K_C = \begin{bmatrix} -\sin\theta_1 & \cos\theta_1 & L \\ -\sin\theta_2 & \cos\theta_2 & L \\ -\sin\theta_3 & \cos\theta_3 & L \end{bmatrix}.$$

2.3. **Kinetics.** The kinetic equation in terms of C is given by

$$A^T M_0 A \ddot{X}_C + A^T M_0 \dot{A} \dot{X}_C = K_C^T F \tag{3}$$

where $\ddot{X}_C$, F, M_0 and A are defined as

$$\begin{aligned} \ddot{X}_C &= \begin{bmatrix} \ddot{x}_C & \ddot{y}_C & \ddot{\theta}_1 \end{bmatrix}^T, \quad F = \begin{bmatrix} f_1 & f_2 & f_3 \end{bmatrix}^T, \\ M_0 &= \begin{bmatrix} M+m & 0 & 0 \\ 0 & M+m & 0 \\ 0 & 0 & I_G \end{bmatrix}, \\ A = K_G^{-1}K_C &= \begin{bmatrix} 1 & 0 & -d\sin(\alpha+\theta_1) \\ 0 & 1 & d\cos(\alpha+\theta_1) \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & p \\ 0 & 1 & q \\ 0 & 0 & 1 \end{bmatrix}. \end{aligned}$$

Here, M is the mass of the SOMW, m is the mass from the patient, I_G is the mass moment of inertia at the position G, and f_1, f_2 and f_3 are the forces exerted by the individual omniwheel motors.

In the next section, a controller is designed based on the model in Equation (3) to ensure that the SOMW follows the reference path.

3. **Controller Design.** The control method is based on an adaptive control law.

Theorem 3.1. *Considering the nonlinear system described in Equation (3) with control of the form*

$$F = K_C^{T^{-1}} \left\{ \hat{M}_{A1}\left(\ddot{X}_d + \lambda\dot{e}\right) + \hat{M}_{A2}\left(\dot{X}_d + \lambda e\right) + \mathrm{K}S \right\} \tag{4}$$

the adaptive law is chosen to be

$$\dot{\hat{\alpha}} = \Gamma H S \tag{5}$$

where

$$S = \dot{e} + \lambda e, \quad e = X_d - X_C = [e_x,\ e_y,\ e_\theta]^T, \quad X_d = [x_{Cd},\ y_{Cd},\ \theta_{1d}]^T,$$

$$\alpha = \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & \alpha_6 \end{bmatrix}^T = \begin{bmatrix} m_1 & m_2 & m_3 & m_4 & m_5 & m_6 \end{bmatrix}^T,$$

$$M_{A1} = A^T M_0 A = \begin{bmatrix} M+m & 0 & (M+m)p \\ 0 & M+m & (M+m)q \\ (M+m)p & (M+m)q & (M+m)d^2 + I_G \end{bmatrix} = \begin{bmatrix} m_1 & 0 & m_2 \\ 0 & m_1 & m_3 \\ m_2 & m_3 & m_4 \end{bmatrix},$$

$$M_{A2} = A^T M_0 \dot{A} = \begin{bmatrix} 0 & 0 & (M+m)\dot{p} \\ 0 & 0 & (M+m)\dot{q} \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & m_5 \\ 0 & 0 & m_6 \\ 0 & 0 & 0 \end{bmatrix},$$

$$H = \begin{bmatrix} \ddot{x}_{Cd} + \lambda_1 \dot{e}_x & \ddot{y}_{Cd} + \lambda_2 \dot{e}_y & 0 \\ \ddot{\theta}_{1d} + \lambda_3 \dot{e}_\theta & 0 & \ddot{x}_{Cd} + \lambda_1 \dot{e}_x \\ 0 & \ddot{\theta}_{1d} + \lambda_3 \dot{e}_\theta & \ddot{y}_{Cd} + \lambda_2 \dot{e}_y \\ 0 & 0 & \ddot{\theta}_{1d} + \lambda_3 \dot{e}_\theta \\ \dot{\theta}_{1d} + \lambda_3 e_\theta & 0 & 0 \\ 0 & \dot{\theta}_{1d} + \lambda_3 e_\theta & 0 \end{bmatrix},$$

$$\lambda = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}, \quad \mathrm{K} = \begin{bmatrix} \mathrm{K}_1 & 0 & 0 \\ 0 & \mathrm{K}_2 & 0 \\ 0 & 0 & \mathrm{K}_3 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} \Gamma_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Gamma_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Gamma_6 \end{bmatrix},$$

where λ, K and Γ are diagonal positive-definite matrices.

Therefore, e converges as $t \to \infty$ and all signals in the closed-loop system are bounded.

Proof: In order to analyze the stability of the closed-loop system, a Lyapunov-like function is specified as

$$V = \left(S^T A^T M_0 A S + \Delta\alpha^T \Gamma^{-1} \Delta\alpha\right)/2 \tag{6}$$

in which the estimation error $\Delta\alpha$ is given by $\Delta\alpha \triangleq \hat{\alpha} - \alpha$, where $\hat{\alpha}$ is an estimate of α.

Differentiating Equation (6) with respect to time and substituting Equations (4) and (5) yields

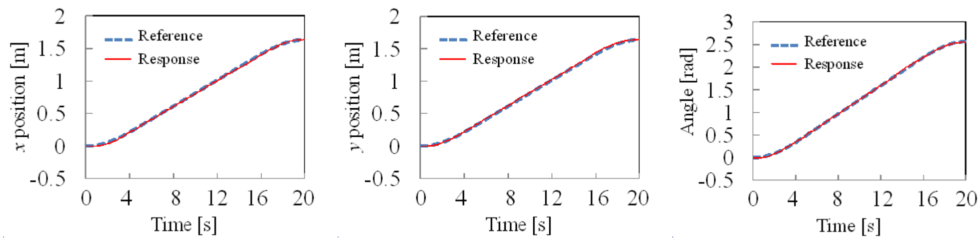
$$\begin{aligned} \dot{V} &= \dot{S}^T A^T M_0 A S/2 + S^T A^T M_0 A \dot{S}/2 + S^T \dot{A}^T M_0 A S/2 + S^T A^T M_0 \dot{A} S/2 \\ &\quad + S^T A^T \dot{M}_0 A S/2 + \Delta\alpha^T \Gamma^{-1} \Delta\dot{\alpha} \\ &= S^T A^T M_0 A \dot{S} + S^T A^T M_0 \dot{A} S + \Delta\alpha^T \Gamma^{-1} \dot{\hat{\alpha}} \\ &= S^T M_{A1} \left(\ddot{X}_d - \ddot{X}_C + \lambda \dot{e}\right) + S^T M_{A2} \left(\dot{X}_d - \dot{X}_C + \lambda e\right) + \Delta\alpha^T \Gamma^{-1} \dot{\hat{\alpha}} \\ &= -S^T \left\{\hat{M}_{A1} \left(\ddot{X}_d + \lambda \dot{e}\right) + \hat{M}_{A2} \left(\dot{X}_d + \lambda e\right) + \mathrm{K} S\right\} \\ &\quad + S^T M_{A1} \left(\ddot{X}_d + \lambda \dot{e}\right) + S^T M_{A2} \left(\dot{X}_d + \lambda e\right) + \Delta\alpha^T \Gamma^{-1} \dot{\hat{\alpha}} \\ &= -S^T \mathrm{K} S + S^T \left(M_{A1} - \hat{M}_{A1}\right) \left(\ddot{X}_d + \lambda \dot{e}\right) \\ &\quad + S^T \left(M_{A2} - \hat{M}_{A2}\right) \left(\dot{X}_d + \lambda e\right) + \Delta\alpha^T \Gamma^{-1} \dot{\hat{\alpha}} \\ &= -S^T \mathrm{K} S \end{aligned} \tag{7}$$

where $S^T A^T \dot{M}_0 A S/2$ is eliminated because M_0 is assumed to be a constant matrix.

In Equation (6), V is positive definite due to the positive definiteness of matrices $A^T M_0 A$ and Γ^{-1}. Hence, V plays the role of a Lyapunov function. Although Equation (7) shows only that the time derivative of V is non-positive definite, $\dot{V} = 0$ would imply $S = 0$. In addition, $S = \dot{e} + \lambda e = 0$ would imply $\dot{e} = 0$ and $e = 0$. Since all the signals in the closed -loop system are bounded and e converges to zero as $t \to \infty$, the designed system is stable.

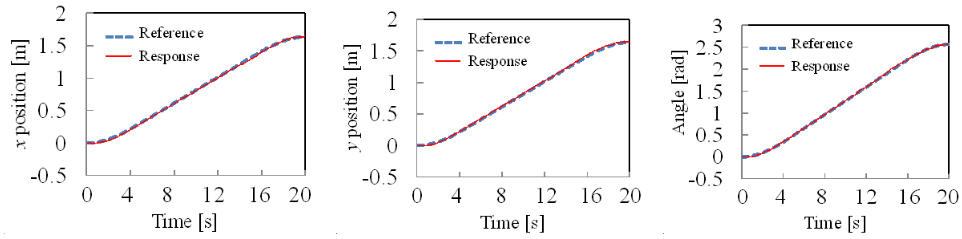
4. **Experimental Evaluation.** In this section, the proposed control algorithm is experimentally evaluated by attempting to make the SOMW follow the correct reference path and orientation angle with and without a load. The position and orientation angle of the SOMW in real time are measured by a camera hung from the roof. In order to thoroughly demonstrate the effectiveness of the proposed method to deal with the load change and COG shift, a load instead of a user is applied to the experiment.

Figure 2 shows the tracking performance of the SOMW over a period of 20 s in terms of the x position, y position and orientation angle θ_1 in the absence of a load. The SOMW starts from the original point. The results indicate that the SOMW can effectively track



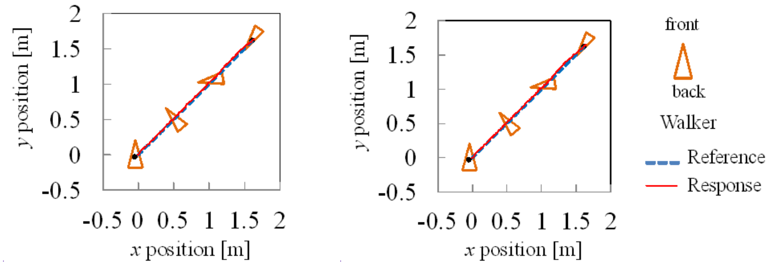
(a) x position (b) y position (c) Orientation angle θ_1

FIGURE 2. Tracking performance without load



(a) x position (b) y position (c) Orientation angle θ_1

FIGURE 3. Tracking performance with load



(a) Without load (b) With load

FIGURE 4. Tracking and orientation of SOMW

even a reference path that is changing with time. The largest error is 0.03 m. Figure 3 shows the results under applied load conditions of $m = 15$ kg, $d = 0.09$ m. Again, it can be seen that the SOMW can effectively track the reference path. In this case also, the largest error is 0.03 m.

The tracking and orientation of the SOMW without and with a load are shown in Figure 4. It can be seen that in both cases the SOMW follows the reference path. The adaptive controller can adapt to parameter uncertainties and it estimates the system parameter α in real time. It is therefore effective for motion control of a SOMW subject to load change and COG shift.

5. **Conclusion.** A SOMW can contribute to the early recovery of walking ability by early starting to build up muscular strength of the lower limbs. In this paper, the kinematics and kinetics of the SOMW are derived. An adaptive control algorithm is proposed for the SOMW in order to minimize path tracking errors caused by load change and COG shift. The algorithm was experimentally evaluated with and without a load and the tracking responses were found to converge rapidly and smoothly. It is therefore well suited to motion control of a SOMW. Future work will focus on the practical application of this control algorithm to SOMWs during patient rehabilitation.

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