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Path Tracking Control of an Omni-directional Walker Considering Pressures from a User *

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***Abstract*—An omni-directional walker (ODW) is being developed to support the people with walking disabilities to do walking rehabilitation. The training paths, which the user follows in the rehabilitation, are defined by physical therapists and stored in the ODW. In order to obtain a good training effect, the defined training paths need to be performed accurately. However, the ODW deviates from the training path in real rehabilitation, which is caused by the variation of the whole system`s parameters due to the force from the user. In this paper, the characteristics of pressures from a user are measured, based on which an adaptive controller is proposed to deal with this problem, and validated in an experiment in which a pseudo handicapped person follows the ODW. The experimental results show that the proposed method can control the ODW to accurately follow the defined path with or without a user.**

I. Introduction

People suffering from walking disabilities are increasing due to accidents or illnesses. Walking rehabilitation is usually necessary for them to recover. At present, walkers are commonly used to assist people with walking disabilities to improve balance ability and muscle strength. Walkers, such as crutches, canes, and parallel bars and folding walkers, only allow a few basic motions.

In the authors` previous studies, an omni-directional walker (ODW) which realizes omni-directional movement is introduced to support people with walking disabilities for walking rehabilitation [1]. In walking rehabilitation, a user follows the movement of the ODW to perform walking training. The training programs are stored in the walker so that rehabilitation can be carried out without the presence of a physical therapist. Its effectiveness in walking rehabilitation has been verified by clinical tests [2].

In walking rehabilitation, the user must precisely follow the reference path prescribed by the physical therapists to get a good training effect. However, the ODW deviates from the reference path due to the users leading to the variations of the system parameters. Adaptive control [3] does not need the exact values of the plant parameters and can adapt to parameter uncertainties by measuring and adjusting the parameters automatically. In previous studies, a nonlinear adaptive controller was developed to deal with load change and center of gravity (COG) shift caused by the users[4,5]. In reference [4,5], we supposed that the load is constant for one user, but is different from user to user. In this paper, the characteristics of pressures imposed on the ODW by a user are measured, and the load and the COG changes for the user are analyzed. An improved adaptive controller is proposed to deal with this problem. Path tracking results are demonstrated by path tracking with and without a user.

The paper is organized as follows: Section II introduces the structure of the ODW and the characteristics of the pressures from the user. Section III demonstrates the mathematical model and the proposed strategy. Section IV shows the experimental results with the proposed controller. Conclusions are provided in Section V.

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II. Structure of ODW and Measurement of Pressure

A. Structure

The structure of the ODW is shown in Fig. 1. The most important feature of the walker is the omni-wheel. The arrangement of four omni-wheels at the bottom of the walker enables the walker to move in any direction while maintaining its orientation. Four force sensors are installed in the armrest for measurement of the pressure from the user. The physical parameters of the ODW are shown in Table.1

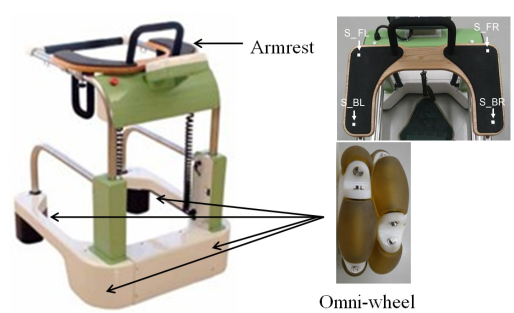


Figure 1. Omni-directional walker

TABLE I. Physical Parameters of the ODW

Parameter	Value	Unit
Height	900–1200	mm
Arm	600	mm
Mass	58	kg
Maximum load	100	kg
Maximum speed	0.25	m/s

B. Measurement of the characteristics of pressure

The variation of the system parameters caused by a user was investigated in a measurement experiment. Four healthy volunteers aged 28-38 yr participated in the experiment. Their right legs were fixed with a knee supporter (allowed bending angle 0°~15°) to simulate people with walking disabilities. Subjects were instructed to follow the movement of the ODW. The experimental environment is shown in Fig. 2. Two kinds of experiments are carried out, one is moving forward and the other is moving rightward. Each subject performed four times for each kind of setting. And the measurement results of the fourth trial of each subject are selected to show the characteristics of load change.

The experimental results are shown in Fig.3 for moving forward and Fig. 4 for moving rightward. In Fig. 3(a), the horizontal axes indicates the time, and the vertical axes indicates the load change imposed on the armrest caused by a user. Load change is vary within a certain range for one subject, and has a great different from the subject to subject. The positions of COG are concentrated on the right and also are different from subject to subject as shown in Fig.3(b). The coordinate system in Fig.4 is the same with that in Fig. 3. We get the similar results with Fig. 3.The change of the load is around the average for one subject. When the subject with his right leg fixed follows the ODW, his arms push the armrest to relieve the burden from his right leg in order to keep balance.

In order to demonstrate the influence of the load change and COG shift, the path tracking results of one subject are given. The path tracking results of S4 are shown in Fig. 5. The solid blue line means that the ODW moves forward to follow the reference path, and the solid red line means moving rightward to follow the reference path with the ODW vertical to the reference. We can find that the ODW deviates from the reference path due to the load changes and COG shifts. The maximum errors are 0.21m on forward movement and 0.56m on rightward movement.

In rehabilitation, the ODW needs to follow the defined path in order to get a training effect. In previous studies, we supposed that the load and the position of COG was not changed for one user within one time training. We designed the adaptive controller focusing on the average characteristic for one user. However, the parameters related to a user vary around the average value. A controller, which can deal with the time-varying load changes and the COG shifts, is necessary to improve the path tracking accuracy in actual walking training.

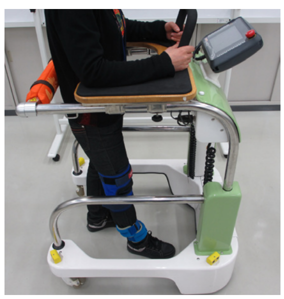
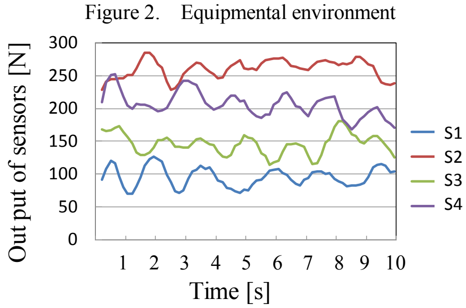
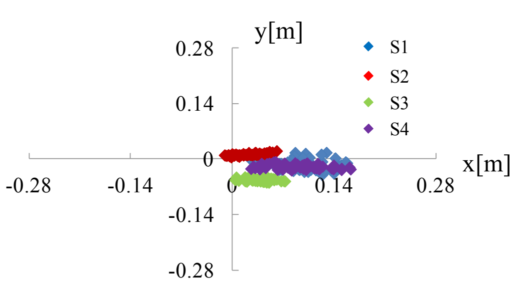


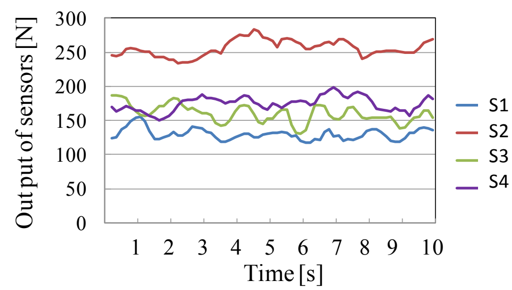
Figure 2. Equipmental environment



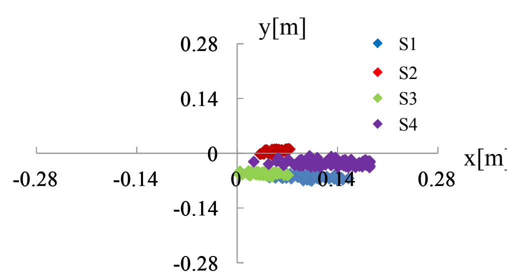
(a) Load change



(b) Position of COG
Figure 3. Forward movement



(a) Load change



(b) Position of COG
Figure 4. Rightward movement

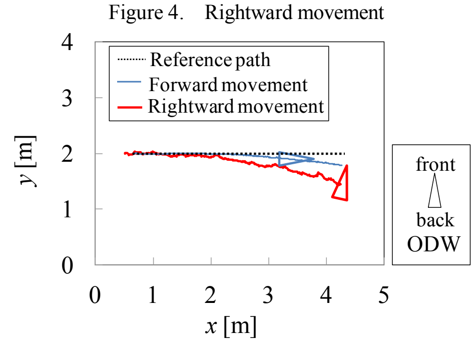


Figure 5. Pathes of S4

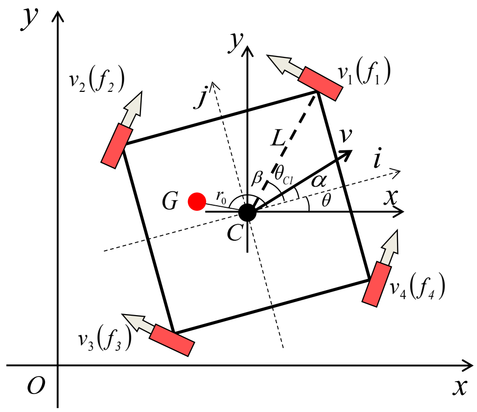


Figure 6. Structural model of omni-directional walker

III. CONTROLLER DESIGN

A. Mathematical model

The coordinate settings and structural model considering load changes and COG shifts caused by a user are shown in Fig. 6. The parameters and coordinate system are as follows:

$\sum(x, y, O)$: Absolute coordinate system.

$\sum(x, y, C)$: Translation coordinate system of the ODW.

$\sum(i, j, C)$: Local coordinate system.

C: Center of the ODW.

θ_{Ci} : Angle between the i-axis and the position of omni-wheel i as measured from the C.

G: COG of the system (including the ODW and equivalent mass).

r_0: Distance between the C of G.

β : Angle between the i-axis and CG.

v : Speed of the ODW.

α : Angle between the i-axis and the direction of v.

v_i : Speed of an omni-directional wheels .

f_i : Force on omni-wheel i.

L : Distance from the C to each omni-wheel.

θ : Angle between the x-axis and the i-axis.

$i = 1,2,3,4$

Using the coordinate system, dynamics analysis is carried out for the nonlinear system. The dynamics equation considering the load changes and the COG shifts is

$$M_0 \cdot \ddot{X} = BF \tag{1}$$

where

$\ddot{X} = [\ddot{x}_G \quad \ddot{y}_G \quad \ddot{\theta}]^T$;

$F = [f_1 \quad f_2 \quad f_3 \quad f_4]^T$;

$$M_0 = \begin{bmatrix} M+m & 0 & 0 \\ 0 & M+m & 0 \\ 0 & 0 & I \end{bmatrix};$$

$$B = \begin{bmatrix} -\sin(\theta+\theta_{C1}) & \cos(\theta+\theta_{C1}) & -\sin(\theta+\theta_{C1}) & \cos(\theta+\theta_{C1}) \\ \cos(\theta+\theta_{C1}) & \sin(\theta+\theta_{C1}) & \cos(\theta+\theta_{C1}) & \sin(\theta+\theta_{C1}) \\ L & -L & -L & L \end{bmatrix}.$$

where M is the mass of the ODW; m is the equivalent mass that the user imposes on the ODW, which varies according to the user's walking disability; and I is the inertia of mass of the whole system. The detail derivation of the dynamics had been introduced in reference [4].

B. Control Strategy

In reference [4], the value of matrix M_0 is constant for a specific user. In this paper, we considering the matrix M_0 variable. Based on this dynamic equation (1), an adaptive controller was proposed to control the ODW accurately following the reference path inspired by Slotine and Li [6]. The stability of the adaptive controller is proved to deal with time-varying load changes and COG shifts caused by the user.

Theorem 3.1. Consider the nonlinear system (1) with a controller

$$F = B^T (BB^T)^{-1}[\hat{M}_0(\ddot{X}_d + \lambda\dot{e}) + KS] \tag{2}$$

and adaptive law

$$\dot{\hat{\alpha}} = \Gamma^{-1} HS.$$
(3)

and the parameters of the adaptive control are

$$\lambda = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}, \quad K = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} \Gamma_1 & 0 & 0 \\ 0 & \Gamma_2 & 0 \\ 0 & 0 & \Gamma_3 \end{bmatrix}.$$

when the elements of matrix $K - \dot{M}_0/2$ are positive. Then, error e converges as time $t \to \infty$, and all signals in the closed-loop system are bounded.

In order to analyze the closed-loop system stability, the Lyapunov-like function candidate is specified as

$$V = \frac{1}{2}(S^T M_0 S + \Delta^T \alpha \ \Gamma \ \Delta\alpha) \tag{4}$$

where $\Delta\alpha \stackrel{\Delta}{=} \hat{\alpha} - \alpha$

Differentiating (4) with respect to time and substituting (2) and (3) yields

$$\begin{aligned} \dot{V}(t) &= S^T M_0 \dot{S} + S^T \dot{M}_0 S/2 + \Delta^T \alpha \ \Gamma \ \Delta\dot{\alpha} \\ &= -S^T KS - S^T(\hat{M}_0 - M_0)[\ddot{X}_d + \lambda\dot{e}] + \Delta^T \alpha \ \Gamma \ \dot{\hat{\alpha}} + S^T \dot{M}_0 S/2 \\ &= -S^T KS + S^T \dot{M}_0 S/2 \\ &= -S^T(K - \dot{M}_0/2)S \end{aligned} \tag{5}$$

In (4), V is positive definite due to the positive definiteness of matrices M_0 and Γ. Hence, V plays the role of a Lyapunov's function. If (5) shows that the time derivative of V is non-positive definite, the designed system is stable. The parameters K need adjusting to make sure that the elements of matrix $K-\dot{M}_0/2$ are positive. In the next section, the proposed method can deal with the time-varying parameters, and the stability can be guaranteed by adjusting the parameters K.

IV. EXPERIMENT

This section shows an experiment in which a pseudo handicapped person follows the ODW with the proposed adaptive controller. We compare it with an experiment in which the ODW run without a user.

A camera is used to record the real-time position of the ODW and feeds it back to the controller. The frame rate is 30 fps. The position of the ODW includes the x and y positions, and the orientation angle θ. Our objective is to control the ODW to follow the reference path. The subjects of the experiment in Section II participated in the experiment. Their right legs were restricted to simulate the person with walking disabilities.

The reference path, an ellipse, is described by

$$\frac{(x_{Gd}-x_0)^2}{a^2}+\frac{(y_{Gd}-y_0)^2}{b^2}=1 \quad (6)$$

where x_0 and y_0 specify the center of the ellipse. In the experiment, $x_0=1.5$ m and $y_0=0.5$ m. The trajectory is described by

$$\begin{aligned} x_{Gd}(t) &= x_0+a\cdot\cos(\pi t/40) \\ y_{Gd}(t) &= y_0+b\cdot\sin(\pi t/40) \\ \theta_d(t) &= 2\pi t/40 \end{aligned} \quad (7)$$

which means that the ODW moves along half of ellipse path within 40s when $a=1.0$ m/s and $b=3.0$ m/s.

The proposed adaptive controller is applied to control the ODW to follow the reference path as shown in equation (7). The parameters shown below are adjusted when the ODW runs without a user.

$$\lambda=\begin{bmatrix}16&0&0\\0&14&0\\0&0&10\end{bmatrix},\ K=\begin{bmatrix}70&0&0\\0&70&0\\0&0&80\end{bmatrix},\ \Gamma=\begin{bmatrix}0.08&0&0\\0&0.30&0\\0&0&4.00\end{bmatrix}.$$

The path tracking results of S4 are shown in Fig.7. The dotted line means reference path. The solid green line is the result that no user condition, and the solid red line means the result that S4 followed the ODW. In Fig. 7, The path tracking error result with a user is almost the same with that without a user. The maximum error on path is 0.08m. The experimental results show that the ODW can follow the reference path accurately even with time-varying parameters.

The characteristics of the pressures from subject S4 are shown in Section II, based on which the change of the inertia matrix $\dot{M}_0$ can be calculate. The elements of $\dot{M}_0$ are smaller than 50 N/s and 12 kg· m^2/s. Then the elements of matrix $K-\dot{M}_0/2$ are positive, and the system is stable. In Fig. 7, although there are no accumulative errors, the accidental errors exist during the experiment, which will be studied in the future.

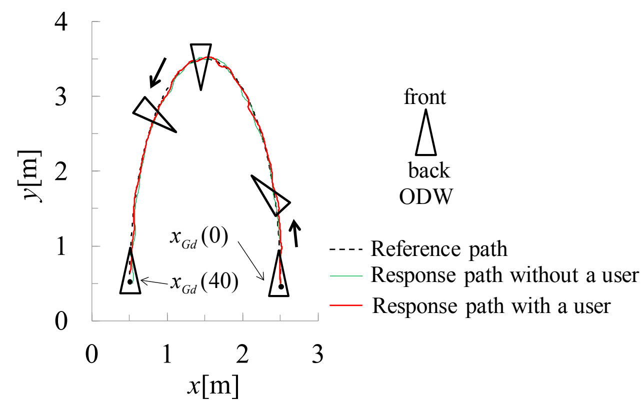


Figure 7. Path traking results

V. CONCLUSION

In rehabilitation with the support of the ODW, the user puts his arms on the armrest, which leads to a low path training accuracy. In order to get a good training effect, the ODW needs to accurately follow the training path. In this paper, the characteristics of pressures from a user`s arms are analyzed, and an adaptive controller is improved to deal with load changes and COG shifts caused by the user. A pseudo handicapped person followed the ODW in the experiment. The experiment results showed a low path tracking error. The improved adaptive controller is effective to deal with the variation of the system parameters.

In this paper, we consider the pressures from a user, but walking training is complicated due to the force interaction between the ODW and the user. Future work will conduct more measurement experiments to abstract the characteristics of force from the users and statistically discuss the effectiveness of the control method.

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