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MOTION CONTROL FOR AN INTELLIGENT WALKING SUPPORT MACHINE

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Abstract. *Walking is a vital exercise for health promotion and fundamental ability necessary for everyday life. Up to now, many robots for walking support or walking rehabilitation of the elderly and the disabled are reported. In this paper, a new omni-directional walking support machine is developed. The machine can realize walking support by following the user's control intention which is detected according to the user's manipulation. However, the motion of the machine is affected by the nonlinear frictions, center-of-gravity (COG) shifts and loads changes caused by users. It is necessary to improve the machine's motion performance to follow the user intention and support the user. Therefore, this paper describes a motion control method based on digital acceleration control to deal with the problem of nonlinear frictions, COG shifts and loads changes. Simulations are executed and the results demonstrate the feasibility and effectiveness of the proposed digital acceleration control method.*

Keywords: Walking support, Omni-directional walker, Digital acceleration control, Centre-of-gravity shift, Nonlinear friction, Load changes

1. **Introduction.** In an aging society with a low birthrate, as is the situation in Japan, people suffering from walking impairment due to illness or accidents are increasing. However, the labor population is in serious shortage [1]. Therefore, in previous studies, the authors and their colleagues have developed an omni-directional walker for rehabilitation of the elderly and the disabled [2]. To make a fast recovery, the walker not only can accomplish forward and backward motions, but also can accomplish right and left motions, oblique motions, rotations, and so on [3,4]. However, in the case that patients cannot be recovered by rehabilitation, developing a robot which can assist them in their independent life is highly desirable to reduce the burden of the families and the society.

We are developing a new intelligent walking support machine which allows omni-directional movement for indoor environment and realizes the walking support by following the user's control intention which is detected according to the user's manipulation. In the walking support, it is necessary to improve the machine's motion performance to follow the user intention and support the users to where they intend to go. However, the machine sometimes strays from the intended direction of the users because of the nonlinear friction in the wheels, center-of-gravity (COG) shifts and load changes caused by users which may cause the danger of hitting obstacles. Therefore, the motion control is very important for the walking support machine to improve the motion accuracy and ensure the safety of the users.

This paper focuses on motion control of the walking support machine considering the nonlinear friction in the wheels, COG shifts and load changes. First, a dynamic model is derived. Second, a digital acceleration control method is proposed to compensate the nonlinear friction, COG shifts and load changes. Finally, linear path-tracking simulations are executed and the results demonstrate the feasibility and effectiveness of the proposed control method.

2. **Modeling of the Walking Support Machine.** The structure of the walking support machine is shown in Figure 1. At each corner of the chassis, positioning one mecanum wheel, which enables the machine to move in any direction while maintain its direction. To develop the control law for the machine, the necessary kinematic and dynamic equations are derived based on the coordinate settings and structural model as shown in Figure 2.

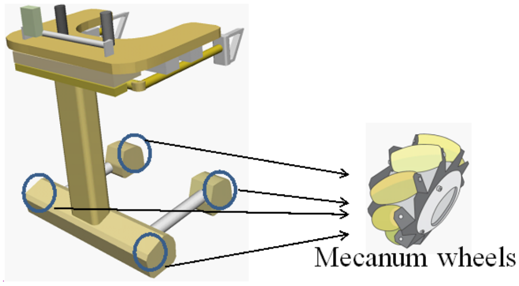


Figure 1. Walking support machine

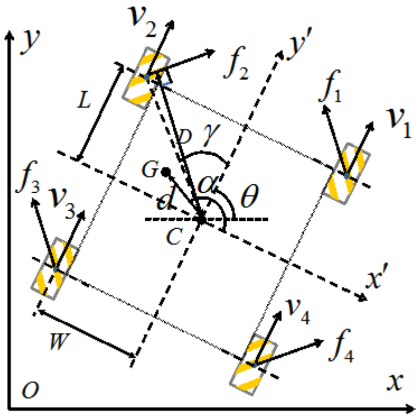


Figure 2. Structural model of the machine

The parameters and coordinate system are as follows:

$\Sigma(x, y, O)$: Absolute coordinate system; $\Sigma(x', y', C)$: Translation coordinate system determined by the movement direction of the walking support machine; $G(x_g, y_g)$: Position of the COG considering the effect of users; $C(x_c, y_c)$: Position of the geometric center; d: Distance between the geometric center and the COG; α: Angle between Cx' and CG; v_i, f_i speed and force of mecanum wheel $(i = 1, 2, 3, 4)$; D: Distance from the geometric center to the drive force f_i; θ: Angle between x-axis and the movement direction of the walking support machine; $2L$: Length of the walking support machine; $2W$: width of the walking support machine.

Using the coordinate system shown in Figure 2, a kinematic analysis is carried out for the four-input, three-output nonlinear system, the kinematic equations are as follows:

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} \cos\theta+\sin\theta & \sin\theta-\cos\theta & L+W \\ \cos\theta-\sin\theta & \sin\theta+\cos\theta & -(L+W) \\ \cos\theta+\sin\theta & \sin\theta-\cos\theta & -(L+W) \\ \cos\theta-\sin\theta & \sin\theta+\cos\theta & L+W \end{bmatrix} \begin{bmatrix} \dot{x}_C \\ \dot{y}_C \\ \dot{\theta} \end{bmatrix} \tag{1}$$

With consideration of the COG shift and load changes caused by users, the dynamic equations of the geometric center are derived as Equation (2)

$$M_0\ddot{X} + C\dot{X} = B(F - f_f) \tag{2}$$

where

$$X = \begin{bmatrix} x_C & y_C & \theta \end{bmatrix}^T, \quad F = \begin{bmatrix} f_1 & f_2 & f_3 & f_4 \end{bmatrix}^T, \quad f_f = \begin{bmatrix} f_{f1} & f_{f2} & f_{f3} & f_{f4} \end{bmatrix}^T,$$

$$M_0 = \begin{bmatrix} M+m & 0 & (M+m)d\sin\alpha \\ 0 & M+m & -(M+m)d\cos\alpha \\ 0 & 0 & I+(M+m)d^2 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & (M+m)d\cos\alpha \\ 0 & 0 & (M+m)d\sin\alpha \\ 0 & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} -\sin(\theta-\pi/4) & \cos(\theta-\pi/4) & -\sin(\theta-\pi/4) & \cos(\theta-\pi/4) \\ \cos(\theta-\pi/4) & \sin(\theta-\pi/4) & \cos(\theta-\pi/4) & \sin(\theta-\pi/4) \\ D-d\cos(\alpha-\gamma) & -[D+d\sin(\alpha-\gamma)] & -[D+d\cos(\alpha-\gamma)] & [D+d\sin(\alpha-\gamma)] \end{bmatrix}$$

where $D = (L^2+W^2)^{1/2}\sin(\pi/4+\gamma)$, $\gamma = \arctan(W/L)$, and M is the mass of the walking support machine; m is the equivalent mass that the user imposes on the walking support machine, which varies according to the user's weight and walking disability; I is the inertia of mass; $f_{fi} = c_i v_i$ $(i = 1, 2, 3, 4)$ represent the nonlinear friction force in the four wheels.

In this paper, the simulation model for the walking support machine is based on the dynamic Equation (2). It can be seen from (2) that the system is a nonlinear system, which has three output x, y and θ controlled by four input forces f_1, f_2, f_3 and f_4.

3. **Controller Design.**

Consider the system dynamic Equation (2) with the digital acceleration control method [5]. Firstly, the control force is kept constant between every time period of length T, kT^+ is the instant after the change of the control torque at time kT.

For a constant time period T, for times kT^+ and kT, we can obtain (3) as

$$\begin{aligned} M_0\ddot{X}[kT] + C\dot{X}[kT] &= B\left(F[kT] - f_f[kT]\right) \\ M_0\ddot{X}[kT^+] + C\dot{X}[kT^+] &= B\left(F[kT^+] - f_f[kT^+]\right) \end{aligned} \tag{3}$$

where $F[(k-1)T^+] = F[kT]$ is the control force during $[(k-1)T^+, kT]$, and $F[kT^+] = F[(k+1)T]$ is the control force during $[kT^+, (k+1)T]$. At times $t = kT^+$ and $t = kT$ the velocity, position and nonlinear friction are constant, but the acceleration is changing. Considering the nonlinear system (2) with control (4)

$$\begin{aligned} F(kT^+) \;=\; & F[(k-1)T^+] + B^T(BB^T)^{-1}M_0\Big\{[\ddot{X}_d(kT^+) - \ddot{X}(kT)] \\ & +K_D[\dot{X}_d(kT^+) - \dot{X}(kT)] + K_P[X_d(kT^+) - X(kT)]\Big\} \end{aligned} \tag{4}$$

where $K_D = \mathrm{diag}(k_{d1}, k_{d2}, k_{d3})$, and $K_P = \mathrm{diag}(k_{p1}, k_{p2}, k_{p3})$ are the speed deviation coefficient and position deviation coefficient, respectively. Here, K_D, K_P are always 3×3 diagonal positive-definite matrices. Let the tracking error of the target trajectory be

$$e(kT^+) = X_d(kT^+) - X(kT^+) \tag{5}$$

Substituting into (4) using (3) and (5) yields Equation (6), and in the short time interval of $[kT^+, (k+1)T]$ Equation (7) holds.

$$\ddot{e}(kT^+) + K_D\dot{e}(kT^+) + K_Pe(kT^+) = 0 \tag{6}$$

$$\begin{aligned} \dot{e}[(k+1)T^+] &= \dot{e}(kT) + \ddot{e}(kT^+)T \\ e[(k+1)T^+] &= e(kT) + \dot{e}(kT^+)T + \ddot{e}(kT^+)T^2/2 \end{aligned} \tag{7}$$

Using (6) and (7) we can obtain

$$\begin{bmatrix} e[(k+1)T^+] \\ \dot{e}[(k+1)T^+] \end{bmatrix} = \begin{bmatrix} I - K_PT^2/2 & (I - K_DT/2)T \\ -K_PT & I - K_DT \end{bmatrix} \begin{bmatrix} e[kT^+] \\ \dot{e}[kT^+] \end{bmatrix} = A \begin{bmatrix} e[kT^+] \\ \dot{e}[kT^+] \end{bmatrix} \tag{8}$$

Here, K_D, K_P are designed to ensure that all eigenvalues of A are within the unit circle, then the system is stable, we can obtain Equation (9). Therefore, the purpose of motion control is accomplished.

$$\lim_{k\to\infty} e(kT) = \lim_{k\to\infty} [X_d(kT) - X(kT)] = 0 \tag{9}$$

4. **Simulation.** In this section, the superiority of digital acceleration control method to deal with the nonlinear friction, COG shift and load changes is verified by linear path-tracking simulations. The physical parameters of the walking support machine in the simulation are given as: $M = 80$ kg, $m = 80$ kg, $W = 0.3$ m, $L = 0.275$ m, $I = 1.31333$ kg·m^2, $\alpha = 2\pi/3$, $d = 0.2$ m, $c_i = 0.2$ kg/s. The trajectory is described by

$$\begin{aligned} x_{cd}(t) &= x_0 + (x_C - x_0)(1 - e^{-at}) \\ y_{cd}(t) &= y_0 + (y_C - y_0)(1 - e^{-at}) \\ \theta_d(t) &= \frac{\pi}{4} \end{aligned} \tag{10}$$

where $a = 0.05\ t^{-1}$, $(x_0, y_0) = (4\text{ m}, 3\text{ m})$ and $(x_C, y_C) = (14\text{ m}, 13\text{ m})$ are the initial and final position of the object trajectory. The initial position $x_c(0) = 3$ m, $y_c(0) = 2$ m and the initial angle $\theta(0) = \pi/2$ rad. The parameters of the digital acceleration controller are adjusted in the simulation for the condition of $f_f = 0$ N, $d = 0$ m and $m = 0$ kg.

Figures 3(a1)-3(d1) show the motion performance of the walking support machine when $f_f = 0$ N, $d = 0$ m and $m = 0$ kg, using the proposed digital acceleration algorithm. This is compared with Figures 3(a2)-3(d2) which show the motion performance of the machine when $f_f \neq 0$ N, $d = 0.2$ m and $m = 80$ kg with no changes to the other parameters. In Figures 3(a1)-3(c1) and Figures 3(a2)-3(c2), the horizontal axes is simulation time (the maximum is 150 s), and the vertical axes are x position, y position, and orientation angle, respectively. Figure 3(d1) and Figure 3(d2) show the tracking and gradient of the machine. In Figures 3(a2)-3(d2), the response curve is similar to that in Figures 3(a1)-3(d1) which indicates that the proposed digital acceleration algorithm allows good motion performance even if nonlinear friction, COG shift and load changes exist.

Although only a linear path is considered in the simulation, the performance with respect to x position, y position, and orientation angle was tested. The above simulation results show that the proposed digital acceleration control method is feasible and effective to deal with the problem of nonlinear friction, COG shift and load changes.

5. **Conclusions.** In this paper, in order to improve the motion performance of a walking support machine, nonlinear friction in the wheels, COG shifts and load changes are considered. A digital acceleration control algorithm is proposed for motion control of the machine. Simulations are executed and the results demonstrate the feasibility and effectiveness of the proposed control method.

REFERENCES

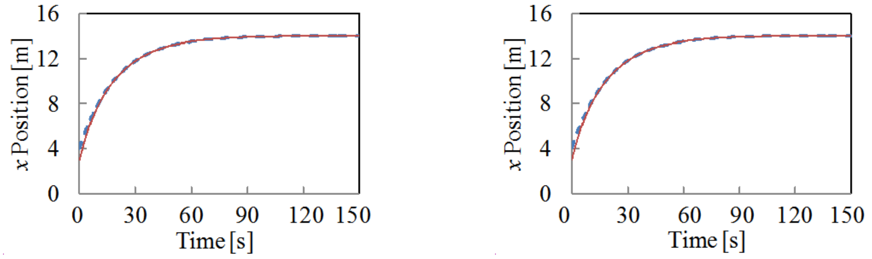
[1] R. P. Tan, S. Y. Wang, Y. L. Jiang, K. Ishida and M. Nagano, Motion control of an omni-directional walker using adaptive control method, *ICIC Express Letters*, vol.4, no.6(A), pp.2195-2199, 2010.

[2] S. Y. Wang, K. Kawata, K. Ishida, H. Yamamoto and T. Kimura, Omni-directional mobile walker for rehabilitation of walking, *The 17th Society of Life Support Technology*, pp.48, 2001 (in Japanese).

[3] Y. Nemoto, S. Egawa, A. Koseki, S. Hattori, T. Ishii and M. Fujie, Power-assisted walking support system for elderly, *Proc. of the 20th Annual International Conference of IEEE Engineering in Medicine and Biology Society*, vol.5, pp.2693-2695, 1998.

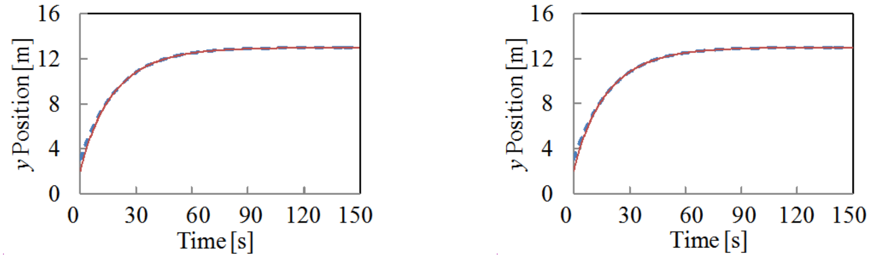
[4] S. Y. Wang, K. Kawata, Y. Inoue, K. Ishida and T. Kimura, Omni-directional mobile walker for rehabilitation of walking which can prevent tipping over, *Japan Society of Mechanical Engineers Symposium on Welfare Engineering*, pp.145-146, 2003.

[5] S. Y. Wang, T. Tsuchiya and Y. Hashimoto, The digital acceleration control method of robot manipulator, *Proc. of the 1st Symposium on Robot Robotics Society of Japan*, vol.1, pp.7-12, 1991 (in Japanese).



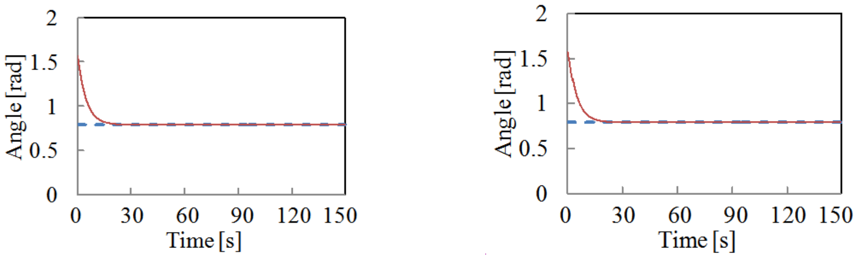
(a1) x position $f_f = 0$ N, $m = 0$ kg, $d = 0$ m

(a2) x position $f_f \neq 0$ N, $m = 80$ kg, $d = 0.2$ m



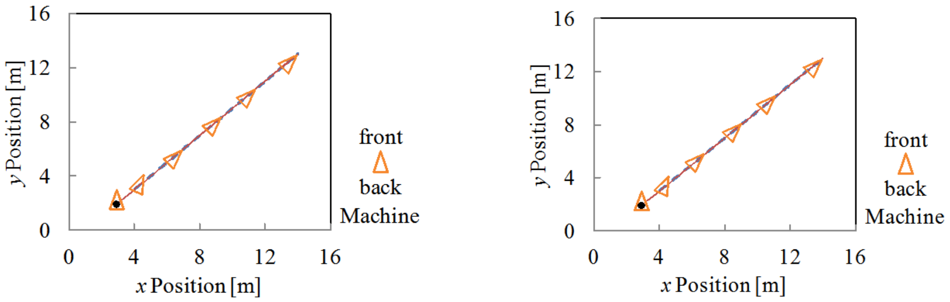
(b1) y position $f_f = 0$ N, $m = 0$ kg, $d = 0$ m

(b2) y position $f_f \neq 0$ N, $m = 80$ kg, $d = 0.2$ m



(c1) Angle $f_f = 0$ N, $m = 0$ kg, $d = 0$ m

(c2) Angle $f_f \neq 0$ N, $m = 80$ kg, $d = 0.2$ m



(d1) Tracking and gradient results $f_f = 0$ N, $m = 0$ kg, $d = 0$ m

(d2) Tracking and gradient results $f_f \neq 0$ N, $m = 80$ kg, $d = 0.2$ m

Figure 3. Simulation results of digital acceleration controller