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IMPROVING THE MOTION PERFORMANCE FOR AN INTELLIGENT WALKING SUPPORT MACHINE BY RLS ALGORITHM

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Abstract. *To make the old people and handicapped people move easily by themselves, an omni-directional walking support machine (WSM) has been developed. In our previous study, to improve the motion performance of the WSM, a digital acceleration control method has been developed to deal with the nonlinear friction. However, the design of the digital acceleration controller requires to know the exact plant parameters of the WSM which are variable due to center of gravity (COG) shift and load changes. The change of the plant parameters affects the motion performance of the digital acceleration control system. Therefore, in this paper, a discrete-time system identification method using recursive least squares (RLS) algorithm is proposed to online identify the WSM's plant parameters for the digital acceleration controller. Simulations are executed and compared with the digital acceleration controller without using RLS algorithm, and the results demonstrate the feasibility and effectiveness of the proposed control method.*
Keywords: Walking support machine, Digital acceleration control, Recursive least squares, Online identification

1. **Introduction.** In an aging society with a low birthrate, as the situation in Japan, the number of people having difficulty in walking due to illness or accidents is increasing and the number of caregiver labor is decreasing. Walking is a fundamental ability necessary for daily life and a vital exercise for health promotion [1]. To make daily life convenient and maintain body healthy, it is essential for the people with walking disabilities to continue walking every day [2]. To solve the labor shortage problem and to reduce the social burden, an intelligence walking support machine (WSM) has been developed in the authors' lab. This WSM allows omni-directional movement in an indoor environment and realizes the walking support by moving to the direction the user is intending to go according to the user's manipulation.

To keep availability of the WSM and ensure security for users, it is necessary to guarantee the motion performance of the WSM. Therefore, in our previous study, a digital acceleration control method has been developed to compensate for the nonlinear friction [3]. However, the design of the digital acceleration control method requires the exact plant parameters of WSM which are variable due to center of gravity (COG) shifts, load change and other uncertainties. The change of the plant parameters will affect the motion performance of the digital acceleration control system. There are many methods that could be used to online identify the plant parameter. In this paper, a discrete-time system identification method using recursive least squares (RLS) algorithm is used to identify the WSM's plant parameters because the RLS algorithm has a fast convergence rate which is important especially when the parameters are changing rapidly.

This paper is organized as follows. Section 2 describes the structure of the WSM, and derives a dynamic model considering the COG shifts and load change. Section 3 designs a digital acceleration controller for the WSM. The plant parameters required in the digital acceleration controller are identified by RLS algorithm in Section 4. Section 5 shows simulations of the proposed method. The simulation results show that the proposed control method is feasible and effective. A conclusion is given in Section 6.

2. **Modeling of the WSM.** The structure of the WSM is shown in Figure 1. Four mecanum wheels are positioned at each corner of the chassis, which enables the WSM to move in any direction while maintaining its orientation. To develop the control law for the WSM, the necessary dynamic equations are derived based on the coordinate settings and structural model as shown in Figure 2.

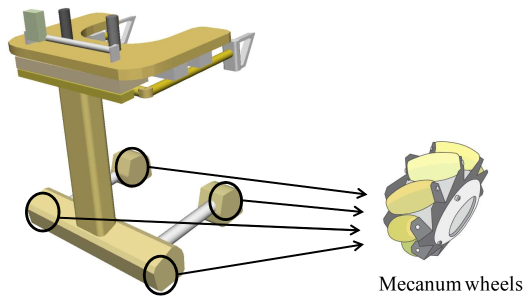


FIGURE 1. Walking support machine

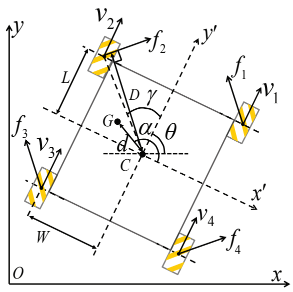


FIGURE 2. Structural model of the machine

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 direction of the WSM;
$G(x_g, y_g)$: Position of COG;
$C(x_c, y_c)$: Position of geometric center;
d: Distance between geometric center and COG;
α: Angle between Cx' and CG;
v_i, f_i speed and driving force of each mecanum wheel ($i = 1, 2, 3, 4$);
D: Distance from geometric center to driving force f_i;
θ: Angle between x-axis and movement direction of the WSM;
$2L$: Length of the WSM;
$2W$: Width of the WSM.

Using the coordinate system shown in Figure 2, with consideration of the COG shift and load changes caused by users, the dynamic equations at the geometric center are derived as Equation (1)

$$\begin{bmatrix} J_0 & 0 & J_1 \\ 0 & J_0 & -J_2 \\ 0 & 0 & J_3 \end{bmatrix} \begin{bmatrix} \ddot{x}_c \\ \ddot{y}_c \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} 0 & 0 & J_2 \\ 0 & 0 & J_1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{\theta} \end{bmatrix} = B(F - f_f) \tag{1}$$

where

$$J_0 = M + m, \quad J_1 = (M+m)d\sin\alpha, \quad J_2 = (M+m)d\cos\alpha, \quad J_3 = I + md^2$$

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

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

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

In this paper, the simulation model for the WSM is based on the dynamic Equation (1). It can be seen from (1) that the system is a nonlinear system, which has three outputs x_c, y_c and θ controlled by four input forces f_1, f_2, f_3 and f_4.

3. **Controller Design.** Considering the system dynamic Equation (1) with the digital acceleration control method [4], the dynamic Equation (1) are rewritten in matrix form as

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

where

$$M_0 = \begin{bmatrix} J_0 & 0 & J_1 \\ 0 & J_0 & -J_2 \\ 0 & 0 & J_3 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & J_2 \\ 0 & 0 & J_1 \\ 0 & 0 & 0 \end{bmatrix}$$

Firstly, the control force is kept constant between every time period of length T. Here, T is the sampling interval of the control force, and 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

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

where $F[kT] = F[(k-1)T^+]$ is the control force during $[(k-1)T^+, kT]$, and $F[kT^+]$ is the control force to be designed during $[kT^+, (k+1)T]$. When the control force has a change from time kT to kT^+, the acceleration is changed. However, the velocity, position and nonlinear friction are still the same by integral characteristic. Based on Equation (3), the control input is designed as follows:

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

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. It is can be seen from Equation (4) that the control force contains the nonlinear friction by using the previous sampling period's control force and acceleration. Therefore, this controller is effective to deal with the nonlinear friction.

4. **Parameter Identification.** Equation (4) shows that the design of the acceleration controller requires the plant parameters M_0 which is a variable due to the COG shifts and load changes. In this section, the plant parameters of the WSM will be identified by the RLS algorithm. Firstly the dynamic Equation (2) is rewritten as follows:

$$Y\hat{J} = BF \tag{5}$$

where Y is defined as

$$Y = \begin{bmatrix} \ddot{x}_c & \ddot{\theta} & \dot{\theta} & 0 \\ \ddot{y}_c & \dot{\theta} & -\ddot{\theta} & 0 \\ 0 & 0 & 0 & \ddot{\theta} \end{bmatrix}$$

and $\hat{J}$ is the estimate of the plant parameter M_0 and C shown as follows:

$$\hat{J} = \begin{bmatrix} \hat{J}_0 & \hat{J}_1 & \hat{J}_2 & \hat{J}_3 \end{bmatrix}^T$$

Based on Equation (5), the RLS algorithm is given as follows

$$\hat{J}(k) = \hat{J}(k-1) + K(k)[BF(k) - Y(k)\hat{J}(k-1)] \tag{6}$$

$$K(k) = P(k-1)Y^T(k)[I + Y(k)P(k-1)Y^T(k)]^{-1} \tag{7}$$

$$P(k) = [I - K(k)Y(k)]P(k-1) \tag{8}$$

where $P(k)$ is a 4×4 matrix, and $K(k)$ is a 4×3 matrix.

In summary, the RLS algorithm can be described by the following steps:

Step 1: Set the initial values $\hat{J}(0)$, $P(0)$, $Y(0)$.

Step 2: Calculate the current gain $K(k)$ based on $P(k-1)$ and current signal $Y(k)$ according to Equation (7), and update the estimate of the plant parameter vector $\hat{J}(k)$ (6) based on its previous value $\hat{J}(k-1)$, current gain $K(k)$, signal $Y(k)$ and $BF(k)$.

Step 3: Update $P(k)$ (8) based on its previous value $P(k-1)$, current signal $Y(k)$ and current gain $K(k)$.

Step 4: Set $k \to k+1$ and return to Step 1 to obtain the new $\hat{J}(k)$.

In simulation, the values of the plant parameters are online identified by repeating the four steps above.

5. **Simulation.** In this section, simulations are conducted using the proposed controller to verify the RLS algorithm. As usual, walking supporting task for WSM is a point to point assignment. Here, the WSM is assumed to follow a circular trajectory. To verify the omni-directional feature of the WSM, the orientation angle is set to be constant as $\pi/2$ rad. The trajectory to be followed is described as

$$\begin{aligned} x_{cd}(t) &= x_0 + r\cos\sigma(t) \\ y_{cd}(t) &= y_0 + r\sin\sigma(t), \quad \sigma(t) = \begin{cases} \frac{4\pi}{t_0^2}t^2 & 0 \le t \le \frac{t_0}{2} \\ 2\pi - \frac{4\pi}{t_0^2}(t-t_0)^2 & \frac{t_0}{2} \le t \le t_0 \end{cases} \\ \theta_d(t) &= \frac{\pi}{2} \end{aligned} \tag{9}$$

$(x_0, y_0) = (5\text{m}, 5\text{m})$ specifies the center of the circle, $r = 4\text{m}$ is the radius, the parameter t_0 can be changed to modify the moving speed of the WSM, and here t_0 is set as 150s. The WSM's initial position is: $x_c(0) = 8\text{m}$, $y_c(0) = 4\text{m}$ and initial angle is: $\theta(0) = 0$ rad. The physical parameters of the WSM are shown in Table 1.

In simulations, the plant parameter M_0 is online identified by RLS algorithm. The initial values of $\hat{J}$, P and Y are set as: $\hat{J}(0) = \begin{bmatrix} 0.01 & 55 & -0.01 & 0.01 \end{bmatrix}^T$, $P(0) = \text{diag}(1, 1, 1, 10000)$, $Y(0) = \mathbf{0}$. To verify the effectiveness of RLS algorithm in improving the motion performance for WSM, the proposed control method is compared with the

Table 1. Physic parameters of the WSM

Symbol	Quantity	Value and Unit	Symbol	Quantity	Value and Unit
H	height	840-1240mm	M	mass	80kg
$2W$	width	600mm	m	Maximum load	80kg
$2L$	length	450mm	I	Inertia of mass	1.3kg·m^2

digital acceleration controller without the RLS algorithm. The parameters of the two digital acceleration controllers are manually adjusted in simulation assuming that there are no load changes, and the COG is the same as the geometric center. The parameters of the two controllers are the same as: $K_D = \text{diag}(3, 3, 3)s^{-1}$ and $K_P = \text{diag}(0.6, 0.6, 0.6)s^{-2}$.

Figure 3 shows the estimated results of J_0 , J_1, J_2 and J_3 using RLS algorithm. The final values are: $\hat{J}_0 = 79.753\text{kg}$, $\hat{J}_1 = 1.020\text{kg}\cdot\text{m}^2$, $\hat{J}_2 = -0.157\text{kg}\cdot\text{m}^2$, $\hat{J}_3 = 1.293\text{kg}\cdot\text{m}^2$ under the condition $m = 0\text{kg}$, $d = 0\text{m}$; $\hat{J}_0 = 159.754\text{kg}$, $\hat{J}_1 = 27.938\text{kg}\cdot\text{m}^2$, $\hat{J}_2 = -15.692\text{kg}\cdot\text{m}^2$, $\hat{J}_3 = 4.498\text{kg}\cdot\text{m}^2$ under the condition $m = 80\text{kg}$, $d = 0.2\text{m}$, which demonstrates that all of the identified values can be very close to the true values. The result suggests that the RLS algorithm is effective to indentify the plant parameters of the WSM.

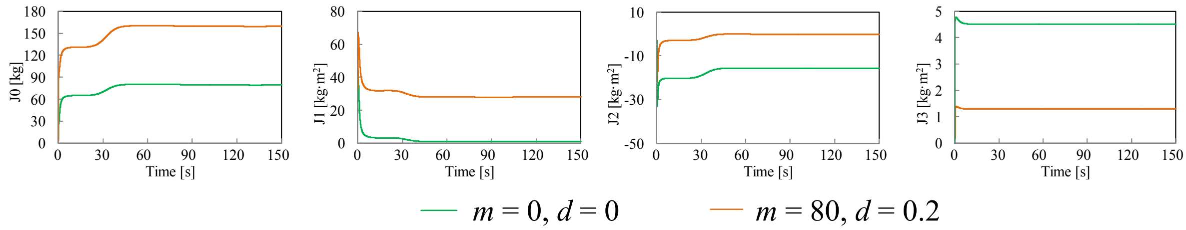


FIGURE 3. The estimated results of J_0, J_1, J_2, J_3

Figure 4 shows the trajectory tracking and gradient of the WSM in the xy plane using the proposed control method. It suggests that the WSM can successfully track the desired trajectory with a constant orientation angle by using the proposed control method under the condition whether the COG shift and load change are considered or not.

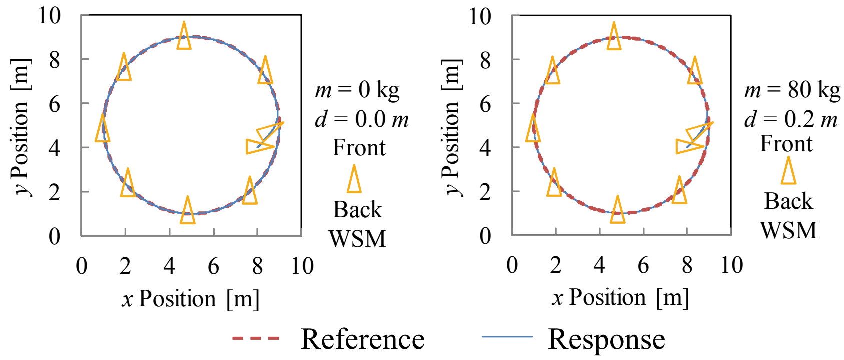
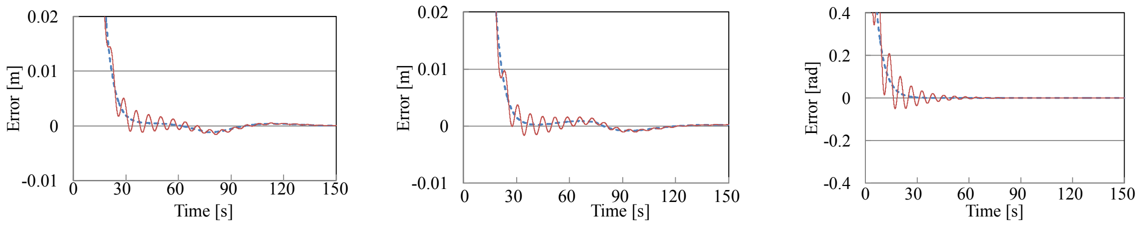


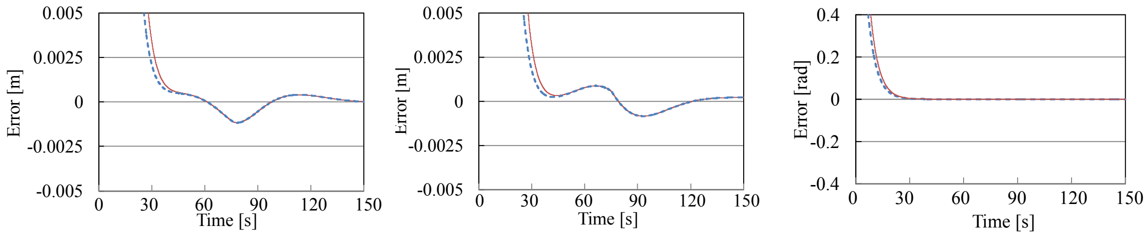
FIGURE 4. Tracking and gradient of WSM

Figure 5(a)-(c) show the tracking error of the WSM for the x position, y position, and orientation angle θ using the digital acceleration controller without RLS algorithm. These are compared with Figure 6(a)-(c), which show the tracking error of the WSM using the digital acceleration controller with RLS algorithm. In Figures 5 and 6, the blue dash lines represent the tracking errors assuming that COG is the same as the geometric center and load is not added. The red solid lines represent the tracking error when the COG is shifting and load is added. It can be seen from the Figure 5 that the tracking error of WSM has a big fluctuation when the load is added and COG is shifting. On the contrast, Figure 6 shows that the tracking error of WSM is almost the same no matter whether the COG shift or load changes are considered or not. These results show that the RLS algorithm is effective to improve the motion performance for the digital acceleration control system especially for condition of that the parameters changes caused by COG shifts and load changes. Simulations suggest that digital acceleration controller with RLS algorithm can improve the performance of path tracking.



(a) x position (b) y position (c) orientation angle

FIGURE 5. Tracking error of x, y position and orientation angle using digital acceleration controller without RLS algorithm



(a) x position (b) y position (c) orientation angle

FIGURE 6. Tracking error of x, y position and orientation angle using digital acceleration controller with RLS algorithm

6. **Conclusions.** In this paper, an RLS algorithm is designed to online identify the plant parameters for the digital acceleration controller to improve the motion performance for a WSM. Simulations are executed and the results demonstrate the feasibility and effectiveness of the RLS algorithm.

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