Control Method Examination of Two-Wheeled Walker for Walking Assistance

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***Abstract*—A completed hardware and performance test results of a two-wheeled walker to support the elder in walking are presented in this paper. The robot is based on the inverted pendulum which is linearized by utilizing the lie algebra method. A nonlinear disturbance observer is used to estimate the disturbance torque from a user to control the rotational motion of the robot. A very good performance of the designed controller of the two-wheeled walker is verified by experimental results which show that the two-wheeled walker is really effective to support the elder or disable in walking or standing.**

***Index Terms*—Inverted pendulum, nonlinear disturbance observer, assist devices, two-wheeled walker.**

I. Introduction

ASSISTANT devices in walking or standing become more and more necessary in modern life when the population is aging. Higher requirements for these devices also increase. The assistant devices with self-balancing, operation in a long time without charging, force support, comfort are expected. The proposed two-wheeled walker in this paper meets the above-mentioned requirements.

Papers [1]–[4] proposed an assistant device based on the inverted pendulum for walking. However, its structure is complicated, not easy to use, and sometimes dangerous because it is difficult to control the speed of the device. Moreover, it cannot support to lift the whole body of the user.

The authors in [5]–[9] have presented a body weight support wearable device based on a couple of motors to assist patients to practice walking. These wearable devices are too heavy and uncomfortable for elderly or disabled people. Another robotic cane for walking assistance was presented in [10]–[12], completed hardware of this robotic cane was shown. However, this robotic cane is not really safe for users because there is the only contact point between the cane and the ground. Besides, it also cannot support the whole body of the user.

To control the motion of nonlinear systems, a nonlinear disturbance observer based on dynamic surface control to stabilize the system was proposed in [13], [14]. But, the results did not show the performance of the system in controlling the motion of their robot and the rotation motion control was not discussed, which is very important to help the user walk easily.

To solve these above-mentioned problems, in this paper, a nonlinear disturbance observer is utilized to estimate the human force applied to the two-wheeled walker to control not only the straight motion but also the rotation motion of the robot. Thanks to this, the user and the two-wheeled walker easily move together. Especially, the hardware of the two-wheeled walker is improved with a U-shaped handle so that it can lift the whole body of the user.

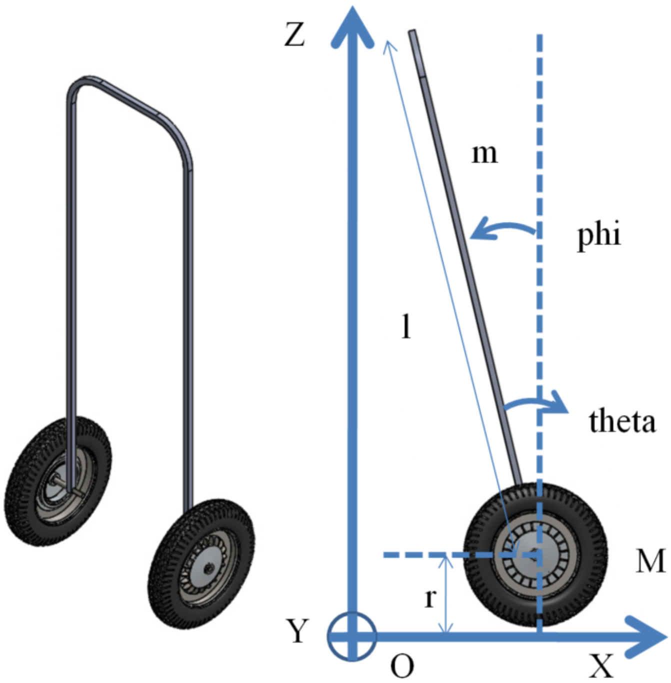


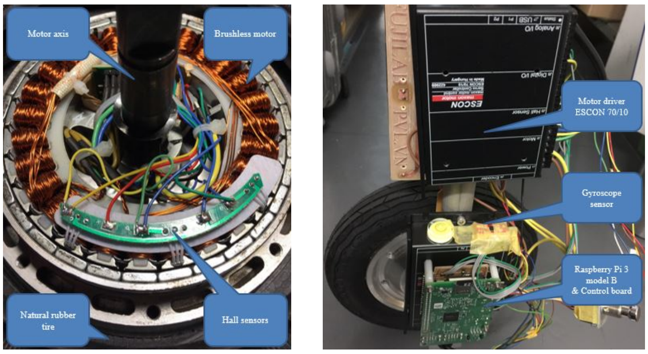
Fig. 1. The two-wheeled walker based on an inverted pendulum mode.

In this paper, the contents are organized as follows: In Section II, the hardware of the two-wheeled walker. Section III presents motion equations of the two-wheeled walker, and the application of the nonlinear disturbance observer in controlling the rotation motion. The high performance of the two-wheeled walker is verified in Section IV by experimental results on a real user.

II. The hardware of a two-wheeled walker

Firstly, the hardware of the two-wheeled walker as shown in Fig. 1 is designed by the Solidworks software and then is manufactured.

The two-wheeled walker consists of a U-shaped frame where the user can hold to be supported, two wheels with an in-wheel electric motor including a natural rubber tire, a battery pack, a controller, a gyroscope sensor MPU6050 and two motor drivers as shown in Fig. 2.



a) b)

Fig. 2. Hardware of the two-wheeled walker: (a) in-wheel electric motor; (b) motor driver (ESCON 70/10).

The U-shaped frame is made by stainless steel pipe with a thickness of 2 mm. By using a key holder on both sides of the frame, the height of the walker can be adjusted easily. The natural rubber tire allows strong torques and gives a comfortable feeling for users due to the cancellation of vibrations. The in-wheel electric motor not only works as a motor but also includes three hall sensors which determine the rotation motion of the motor, speed, and velocity of the walker.

The battery pack comprises 10 cells of 3.7V/3200mAh lithium-ion batteries in series to make a maximum power supply of 42V when it was fully charged as shown in Fig. 2(b). An electric power converter board is used to make a 5V/3A output to supply a controller. This board including LM2597HV is directly supplied from this battery pack of 42V. The 5V/3A output is working well with Raspberry Pi 3 model B+ which works as the controller.

The Raspberry Pi 3 model B+ is based on the raspbian OS for C/C++ coding and controls the system in the real-time.

Two motor drivers (ESCON 70/10) are utilized to control the motion of the walker by using the current control method. This motor driver can control the current of the motor from -10A to 10A. However, we limit it at 5A to make sure the walker work safely for the user and itself. Moreover, the gyroscope sensor MPU6050 is used to calculate the angle and the velocity of the rod of the two-wheeled walker, that is an important value to control the motion of the two-wheeled walker.

III. Force Analysis and System Equations of the Two-Wheeled Walker

This section analyzes the motion of the two-wheeled walker following the users behaviors.

A. A two-wheeled walker motion equations

A motion of the two-wheeled walker based on an inverted pendulum modeling as shown in Fig. 1 can be determined by using the Lagrangian equation as below:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = \tau - d \tag{1}$$

where L is the Lagrangian, q and d is the generalized coordinate and disturbance vector corresponds to ϕ and θ respectively. H_{ij} is an element of the inertia matrix, b_i is a nonlinear term.

TABLE I
Explanation of Symbols

Explanations	***Symbol***	***Unit***
Rotational kinetic energy of wheel	T_1	J
Inertia of rod	J_ϕ	kg·m^2
Inertia of wheel	J_θ	kg·m^2
Viscous friction coefficient of rod	D_ϕ	N.m.s/rad
Viscous friction coefficient of wheel	D_θ	N.m.s/rad
Length of rod	l	m
Mass of rod	m	kg
Mass of wheel	M	kg
Actuation torque	τ	N.m
Gravitational acceleration	g	m/s^2
Radius of wheel	r	m
Angle of the rod	ϕ	rad
Angle of the wheel	θ	rad
Disturbance according to ϕ	d_1	N.m
Disturbance according to θ	d_2	N.m

The transfer function matrix of the robot used to analyze the motion of the two-wheeled walker is as follows:

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -d_1 \\ \tau - d_2 \end{bmatrix} \tag{2}$$

where, the elements of the motion equations of the two-wheeled walker modeling can be calculated by (3)-(7):

$$H_{11} = J_\theta + (M+m)\,r^2 + 2mrl\cos\phi + J_\phi + ml^2 \tag{3}$$
$$H_{12} = H_{21} = -J_\theta - (M+m)\,r^2 - mrl\cos\phi \tag{4}$$
$$H_{22} = J_\theta + (M+m)\,r^2 \tag{5}$$
$$b_1 = -\dot{\phi}^2 mrl\sin\phi - mgl\sin\phi + D_\phi\dot{\phi} \tag{6}$$
$$b_2 = \dot{\phi}^2 mrl\sin\phi + D_\theta\dot{\theta} \tag{7}$$

From (2), the output torque will apply to a motor axis to help the walker to move is given by:

$$\tau = (H_{22} - \frac{H_{12}H_{21}}{H_{11}})u - \frac{H_{21}}{H_{11}}b_1 + b_2 - d_2 \tag{8}$$

B. Lie algebra method to the linearize of a nonlinear system

From these motion equations of the two-wheeled walker, we can easily recognize that this system is a nonlinear system.

We define functions given in (9) and (10). We then use the Lie algebra method to linearization of the nonlinear systems:

$$\dot{x} = f(x) + g(x)u \tag{9}$$
$$y = h(x) \tag{10}$$

Then, Lie algebra method is expressed as follows:

$$L_f h(x) = \sum_{i=1}^{n} \frac{\partial h}{\partial x_i} f_i(x) = \frac{\partial h}{\partial x}(x) f(x) \tag{11}$$

The derivative of y by t is expanded as follows:

$$\frac{dy}{dt} = \frac{\partial h}{\partial x}\frac{\partial x}{dt} = \frac{\partial h}{\partial x}(f(x) + g(x)u) = L_f h(x) + L_g h(x)u \tag{12}$$

Combined with a law as (13), $r < n$:

$$\begin{cases} L_g L_f{}^{(r-1)} h \neq 0 \\ L_g h = L_g L_f h = L_g L_f{}^2 h = ... = L_g L_f{}^{(r-2)} h = 0 \end{cases} \tag{13}$$

We extend the equations of y by t as shown in (14)-(16):

$$\dot{y} = L_f h \tag{14}$$
$$\ddot{y} = L_f{}^2 h \tag{15}$$
$$\vdots$$
$$y^{(r)} = L_f{}^r h(x) + L_g L_f{}^{(r-1)} h(x) u \tag{16}$$

The input value of the controller is calculated by:

$$u = \frac{v - L_f{}^r h(x)}{L_g L_f{}^{(r-1)} h(x)} \tag{17}$$

Therefore, the linear equations of the nonlinear system of the walker are presented as follows:

$$y = \int_0^{\phi} \frac{H_{11}}{H_{12}} d\phi + \theta \tag{18}$$
$$\dot{y} = \frac{H_{11}}{H_{12}}\dot{\phi} + \dot{\theta} \tag{19}$$
$$\ddot{y} = \frac{\partial}{\partial\phi}\frac{H_{11}}{H_{12}}\dot{\phi}^2 - \frac{b_1}{H_{12}} \tag{20}$$
$$y^{(3)} \simeq \frac{\partial^2}{\partial\phi^2}\frac{H_{11}}{H_{12}}\dot{\phi}^3 - \frac{\partial}{\partial\phi}\frac{b_1}{H_{12}}\dot{\phi} - 2(\frac{\partial}{\partial\phi}\frac{H_{11}}{H_{12}})\frac{b_1}{H_{11}}\dot{\phi} \tag{21}$$

For simplicity of programming and analysis, we use expansion with the rank of the derivative of $r = 4$, then the input value of the nonlinear controller is given by:

$$u = \frac{v - L_f{}^4 h(x)}{L_g L_f{}^3 h(x)} \tag{22}$$

C. Nonlinear disturbance observer to estimate the human force applied to the walker

The general motion equation of the two-wheeled walker is rewritten as follows:

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathrm{L}}{\partial \dot{q}}\right) - \frac{\partial \mathrm{L}}{\partial q} = \tau_{all} - d \tag{23}$$

where d is the generalized load torque applied by the user.

The state space of the nonlinear disturbance observer was proposed in Ref. [15], and is represented by:

$$\dot{\xi} = -K\xi + K^2\frac{\partial L}{\partial \dot{q}} + K(\frac{\partial L}{\partial q} + \tau_{all}) \tag{24}$$
$$\hat{d} = \xi - K\frac{\partial L}{\partial \dot{q}} \tag{25}$$

where $\hat{d}$ is the estimated disturbance torque, ξ is the observer state variable, L is the Lagrangian, and K is the gain of the disturbance observer.

The $\frac{\partial L}{\partial \dot{q}}$ are two cases correspond to ϕ and θ as follows:

$$\frac{\partial L}{\partial \dot{\phi}} = H_{11}\dot{\phi} + H_{12}\dot{\theta} \tag{26}$$
$$\frac{\partial L}{\partial \dot{\theta}} = H_{21}\dot{\phi} + H_{22}\dot{\theta} \tag{27}$$

In the two-wheeled walker case, the human force applied on the walker can be processed and estimated by using the nonlinear disturbance observer on the left and right sides of the handle when it supports the user to maintain balance.

Thanks to this estimate, the controller can control the motions of the walker to help the user's rotation more convenient than the traditional method.

D. A basic feedback control to control the system

To control the nonlinear system we use a basic loop with a gain matrix is λ of the controller.

Thus, the coefficient of the controller is defined as:

$$v = -\sum_{i=0}^{3}\lambda_i(y^{(i)} - y_{ref}^{(i)}) \tag{28}$$

This state-feedback gain matrix can be determined by traditional pole-placement methods.

IV. Performance Test of the Two-Wheeled Walker

This section discusses the experimental results of the two-wheeled walker. Measured parameters of the system are given in Table II.

A. Stable by itself in the self-balancing mode

The two-wheeled walker is strongly stable around the equilibrium point in the self-balancing mode as shown in Fig. 3 and Fig. 4.

Fig. 4 shows that the two-wheeled walker strong stable from 0.7 s to the end of the period without any vibrations with the starting point of 0.17 rad.

The pictures in Fig. 3 are taken from a recorded video with a very small angle and position change. This change depends on

TABLE II
MEASURED PARAMETERS OF THE TWO-WHEELED WALKER

Symbol	*Value*	*Unit*
T_s	1e-3	s
D_ϕ	0.01	N.m.s/rad
D_θ	0.01	N.m.s/rad
l	1.13	m
m	50.25	kg
M	3.68	kg
g	9.81	m/s^2
r	0.13	m

a) b)

Fig. 3. The two-wheeled walker standing by itself (a) at the 1^{st} second; (b) at the 45^{th} second.

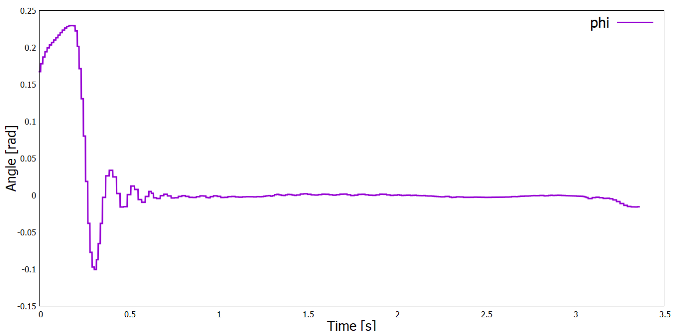


Fig. 4. Angle of the two-wheeled walker in the self-balancing mode.

the bend angle of the contact surface between the two-wheeled walker and the ground. Thus, in the self-balancing mode, the performance of the two-wheeled walker is confirmed. It is effective to support the user to maintain the balance.

B. Support users to stand or to walk

In this section, the performance of the two-wheeled walker is verified when the body weight is put on it (Fig. 5).

Moreover, Fig. 6 show that the walker can move freely on the left and right sides depending on the user behaviors.

Fig. 7 shows responses of the two-wheeled walker in Fig. 5 and Fig. 6 to help the user to stand, move forward, and backward. In these cases, the user holds two hands on both sides of the rod of the walker. Then depending on the estimated force and the angle of the walker, the controller controls the walker to help the user maintain balance when the walker, and the user walk together. For examples, from the starting angle of 0.01 rad, the two-wheeled walker has a small vibration at around 0.2 s after power switch on, it reaches the equilibrium

a) b)

Fig. 5. The status of the two-wheeled walker when the body weight is put on it: (a) the whole body; (b) a half of the body.

a) b)

Fig. 6. The status of the two-wheeled walker when the user walk: (a) move forward; (b) move backward.

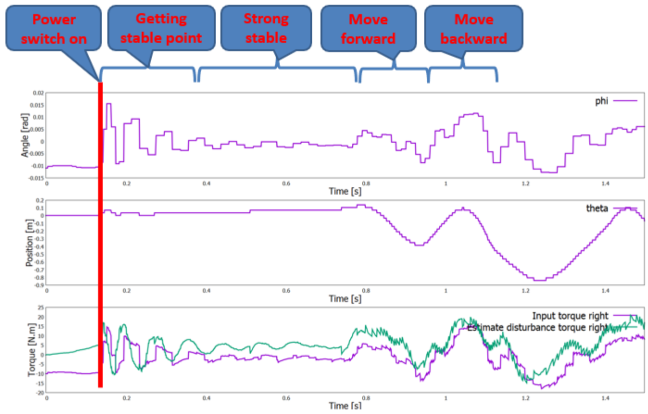


Fig. 7. The position and angle of the two-wheeled walker when supporting the user to walk.

point to support the user maintain balancing with all body weight supported.

Moreover, the user can go forward or backward depending on the behavior of the users hands, then the robot will help them to move ahead from 0.7 s to 0.9 s, and go backward from 1.0 s to 1.1 s as shown in Fig. 7.

Especially, to control the motion of the two-wheeled walker, we use the human force estimation based on the nonlinear disturbance observer. The data in Fig. 8 shows that when the user turns on the right side or the left side, the estimated force is varied accordingly. Depending on this users behavior, the controller will control the robot to help the user move on the right side or the left side easier than other traditional methods.

When the input torque is applied to the handle of the two-wheeled walker, the nonlinear disturbance observer can

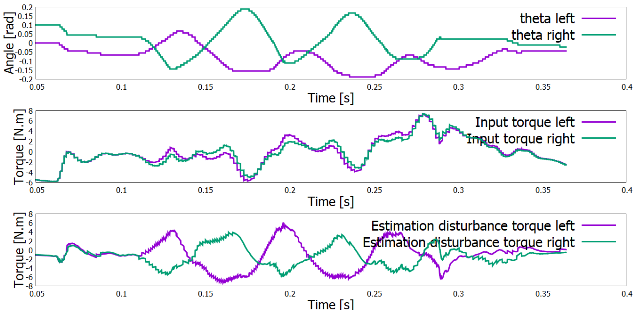


Fig. 8. The angle of the two-wheeled walker when supporting the user turn on the right side, or the left side by estimating the disturbance torque.

estimate the right torque and the left torque applied on the right handle and the left handle of the user. Then, the controller controls the two-wheeled walker move to the right side and the left side more flexible as shown in Fig. 8 corresponding to on the torque estimation result.

The results in the support mode are proved that the two-wheeled walker is really useful to help the older or the disabled to maintain balancing or to walk.

V. Conclusion

The two-wheeled walker based on the inverted pendulum model with the in-wheel electric motor and the natural rubber tire was proposed in this paper. It can support the user effectively to maintain balance and to walk easily when the rotation motion is flexibly controlled depending on the nonlinear disturbance observer. The experimental results were proved that the two-wheeled walker is an excellent candidate for walking assistance for the elder or the disabled.

In future work, we will reduce the size of the two-wheeled walker but increase the battery's working time by using a new motor driver. In addition, we plan to test it in the rehabilitation centers and hospitals.

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