Two-Wheel Cane for Walking Assistance

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***Abstract*—A hardware design and controller of two-wheel cane has been proposed in this paper. Our two-wheel cane has been designed to assist users in maintaining balance as they move. We validated the performance of the controller designed to stabilize the inverted pendulum's balance based on the test results with the designed robot modeling. Experimental results show that two-wheel cane can be most useful to support elderly persons maintain balance.**

Keywords*—Two-wheel cane, robotic cane, inverted pendulum, non-linear disturbance observer, assist devices.

I. Introduction

There are a lot of researches on robots that serve the elderly or disabled people to move, especially the compact type and flexible for the users.

For example, three-wheels robots that serve disabled people to move in the rehabilitation centers studied by the author [1]. However, its design is rather cumbersome and less flexible, the ability to apply it in practice is limited, it is hard to use when the users walk on rugged terrain.

In addition, there are some researches on more compact assistant devices like robotic canes to help users stand or move but their results are just limited on details about robot system design [2] or simulations [3], [4] without experimental results to validate the controller's performance.

In papers [5], [6], experimental results of actual robotic cane modeling were presented. However, its mechanical structure is quite complex by using inverted pendulum model, consequently users may feel uncomfortable when using it.

To overcome the drawbacks from the above studies, we propose a two-wheel cane based on an inverted pendulum model. Parallel with the design of the robot model and the controller are the actual test results with the users.

This paper is composed of four sections: In section II, the two-wheel cane hardware is thoroughly presented. In section III, two-wheel cane mathematical equations including Lie algebra method and nonlinear disturbance observer are solved to evaluate the controller parameters. In section IV, the controller performance discussed on based on experimental results. Finally, the conclusion and future works are described.

II. Hardware of the Two-Wheel Cane

In this section, two-wheel cane hardware is presented. Its design is as shown in Fig. 1.

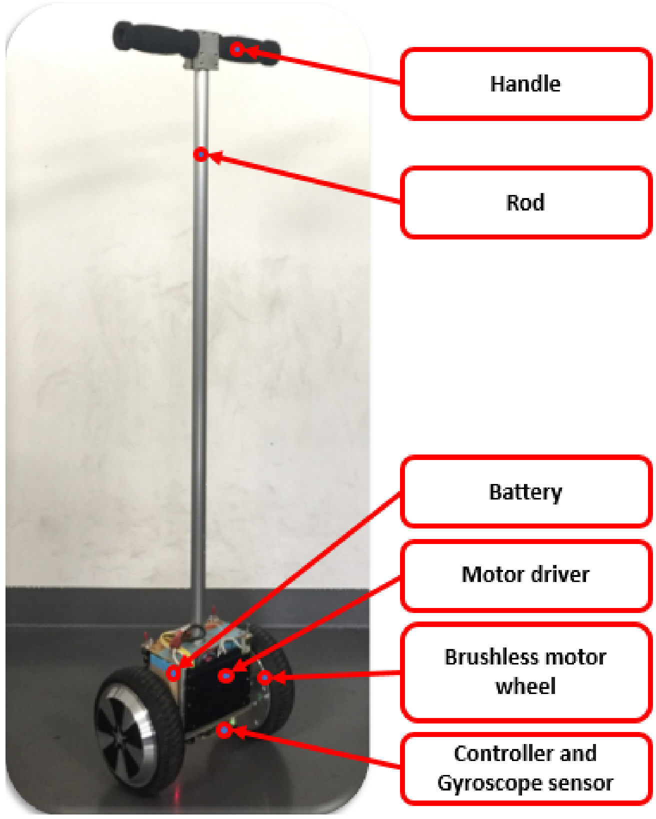

Fig. 1. Two-wheel cane for walking assistance.

It has a handle on the top of the cane, connected to the frame of the two-wheel cane by a rod. This frame is printed by a computer numerical control (CNC) machine. This frame is connected with two natural rubber tire electric wheels (Fig. 2) on the left and right sides. There are two motor drivers on the top of the frame can control the output current of 10 A. At the center of the frame these are Li-ion batteries with capacity of 36V/4400 mAh. These batteries supply power for the two-wheel cane to work in a long time without charging. At the bottom these is a raspberry pi zero controller and a bridge circuit connected to an accelerometer and gyroscope sensor to calculate and control motion of the cane based on our algorithm.

Natural rubber tire electric wheel includes a brushless motor and hall sensors as shown in Fig. 2. Thanks to this structure, the two-wheel cane works well in any environments, and details about them are shown in Table I. Due to the special structure of the wheel without any gearbox types, the two-

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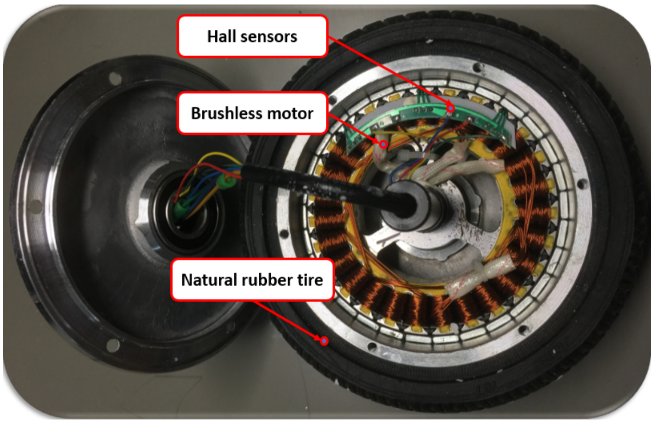

Fig. 2. Natural rubber tire electric wheel included a brushless motor and hall sensors.

TABLE I. PARAMETER OF NATURAL RUBBER TIRE ELECTRIC WHEEL

Symbol	Meaning	Value	Unit
V	Voltage	36	V
P	Output power	250	W
H	Hall sensor	90	p/r
S	Size (thickness x diameter nominal)	46 x 168	mm

wheel cane work without any noises.

Moreover, MPU-6050 accelerometer and gyroscope sensor is used at relatively cheap price. The MPU-6050 devices combine with a 3-axis gyroscope - selectable range up to $\pm$2000 degree/s and a 3-axis accelerometer - selectable range up to $\pm$8 g and 400 kHz, fast mode I^2C (Inter-Integrated Circuit) to communicate with all registers to easily connect with raspberry pi zero w controller.

III. MATHEMATICAL MODEL AND DESIGN OF THE CONTROLLER SYSTEM OF TWO-WHEEL CANE

A. *Mathematical model of two-wheel cane using an inverted pendulum model*

The two-wheel cane in Fig. 3 is basically based on an inverted pendulum model. The rod is l in length, the wheel is r in radius, the mass of wheel is M, and mass of rod is m. By analyzing this system, we use the Lagrange equation to determine the motion of an inverted pendulum as follows:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) - \frac{\partial L}{\partial \phi} + \frac{\partial F_{fr}}{\partial \dot{\phi}} = 0 - d_1 \tag{1}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} + \frac{\partial F_{fr}}{\partial \dot{\theta}} = \tau - d_2 \tag{2}$$

The analysis of the inverted pendulum model was presented by authors in [5], [6]. Similarly, the system motion equation is as follows.

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -d_1 \\ \tau - d_2 \end{bmatrix} \tag{3}$$

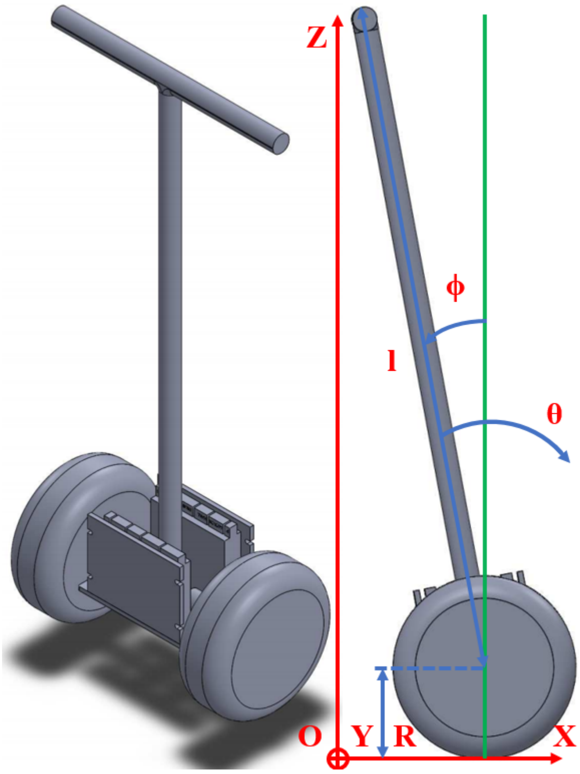

Fig. 3. Two-Wheel Cane System coordinates using Inverted Pendulum.

where,

$$H_{11} = J_\theta + (M+m)\,r^2 + 2mrl\cos\phi + J_\phi + ml^2 \tag{4}$$

$$H_{12} = H_{21} = -J_\theta - (M+m)\,r^2 - mrl\cos\phi \tag{5}$$

$$H_{22} = J_\theta + (M+m)\,r^2 \tag{6}$$

$$b_1 = -\dot{\phi}^2 mrl\sin\phi - mgl\sin\phi + D_\phi\dot{\phi} \tag{7}$$

$$b_2 = \dot{\phi}^2 mrl\sin\phi + D_\theta\dot{\theta} \tag{8}$$

The two-wheel cane needs a force to be applied to the axis motor to move and help users maintain balance. From (3), the torque on the motor axis is given the equation as below:

$$\tau = (H_{22} - \frac{H_{12}H_{21}}{H_{11}})u - \frac{H_{21}b_1}{H_{11}} + b_2 - d_2 \tag{9}$$

B. *Linearization of nonlinear system by Lie algebra method*

From the motion equation of two-wheel cane, we expand it in (10). We easily recognize that this system is a nonlinear system.

$$\dot{x} = \begin{bmatrix} \dot{\phi} \\ \ddot{\phi} \\ \dot{\theta} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} \dot{\phi} \\ -\frac{b_1}{H_{11}} \\ \dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{H_{12}}{H_{11}} \\ 0 \\ 1 \end{bmatrix} u \tag{10}$$

The Lie algebra method to linearize the nonlinear system is one of the best selections to control the inverted pendulum model. This method is defined as a function given in (11) and (12):

$$\dot{x} = f(x) + g(x)u \tag{11}$$
$$y = h(x) \tag{12}$$

After expanding them to find the y function is a linear equation, its derivatives from the first order to the third order can be calculated by (13)-(16).

$$y = \int_0^\phi \frac{H_{11}}{H_{12}} d\phi + \theta \tag{13}$$
$$\dot{y} = \frac{H_{11}}{H_{12}} \dot{\phi} + \dot{\theta} \tag{14}$$
$$\ddot{y} = \frac{\partial}{\partial\phi} \frac{H_{11}}{H_{12}} \dot{\phi}^2 - \frac{b_1}{H_{12}} \tag{15}$$
$$y^{(3)} \simeq \frac{\partial^2}{\partial\phi^2} \frac{H_{11}}{H_{12}} \dot{\phi}^3 - \frac{\partial}{\partial\phi} \frac{b_1}{H_{12}} \dot{\phi} - 2(\frac{\partial}{\partial\phi} \frac{H_{11}}{H_{12}}) \frac{b_1}{H_{11}} \dot{\phi} \tag{16}$$

Obviously, these equations are the linear equations of the nonlinear system to show the motion of the two-wheel cane.

The higher derivatives are, the smoother the system is. But depending on the controller, whether it has enough speed to calculate the motion equations of the system or not. In this case, we use the derivative with the fourth order, which meets the speed to process a basic feedback loop controller to controls this system, and the input value u is given by (17).

$$u = \frac{v - {L_f}^4 h(x)}{L_g {L_f}^3 h(x)} \tag{17}$$

where,

$$L_g {L_f}^3 h(x) = -3 \frac{\partial^2}{\partial\phi^2} \frac{H_{11}}{H_{12}} \frac{H_{12}}{H_{11}} \dot{\phi}^2 + \frac{\partial}{\partial\phi} \frac{b_1}{H_{12}} \frac{H_{12}}{H_{11}} + 2 \frac{\partial}{\partial\phi} \frac{H_{11}}{H_{12}} \frac{H_{12}}{{H_{11}}^2} b_1 \tag{18}$$

$${L_f}^4 h(x) = -\frac{\partial^2}{\partial\phi^2} \frac{b_1}{H_{12}} \dot{\phi}^2 + \frac{\partial^3}{\partial\phi^3} \frac{H_{11}}{H_{12}} \dot{\phi}^4 - 5(\frac{\partial^2}{\partial\phi^2} \frac{H_{11}}{H_{12}}) \frac{b_1}{H_{11}} \dot{\phi}^2 - 2 \frac{\partial}{\partial\phi} \frac{b_1}{H_{12}} \dot{\phi}^2 + \frac{\partial}{\partial\phi} \frac{b_1}{H_{12}} \frac{b_1}{H_{11}} + 2 \frac{\partial}{\partial\phi} \frac{H_{11}}{H_{12}} \left(\frac{b_1}{H_{11}} \right)^2 \tag{19}$$

IV. Experimental Results

A. Stabilization of two-wheel cane by itself

The two-wheel cane is designed with the ability of balance with or without being held by the users. This is a basic working mode of an inverted pendulum. Experiments of the controller on two-wheel cane are recorded by videos, and a frame is cut from the video as shown in Fig. 4.

The angle of two-wheel cane has a relationship with the angle of the cane, which is determined by gyroscope sensor in Fig. 5, the result shows that the two-wheel cane achieves

Fig. 4. Two-wheel cane stability by itself.

a stability point after only 1.5 s with a big tilted angle of the rod around 0.18 rad and remain unchanged until the end of the period.

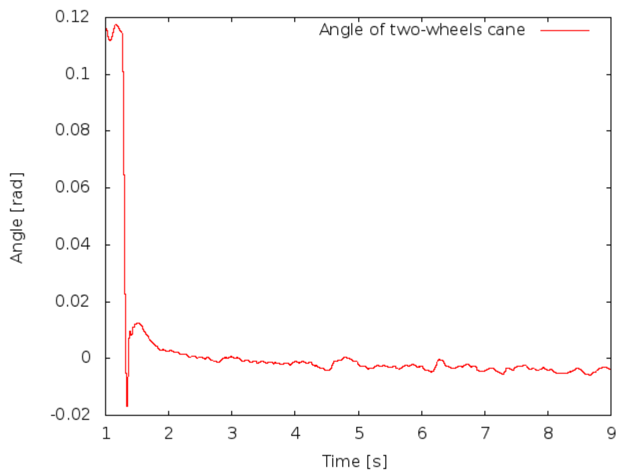

Fig. 5. Angle of two-wheel cane when stability by itself.

This result shows that by using Lie algebra method we can linearize the nonlinear system not only around the zero points as the linear-quadratic regulator (LQR) method but also big tilted angles of the rod. Therefore, this method is really good to control the two-wheel cane to help users maintain balancing when the tilted angle is equal or greater than zero degree.

B. Support users maintain balancing

In the second test, the efficiency of the two-wheel cane is shown by the angle and the feedback position of the two-wheel cane at the same time in Fig. 6.

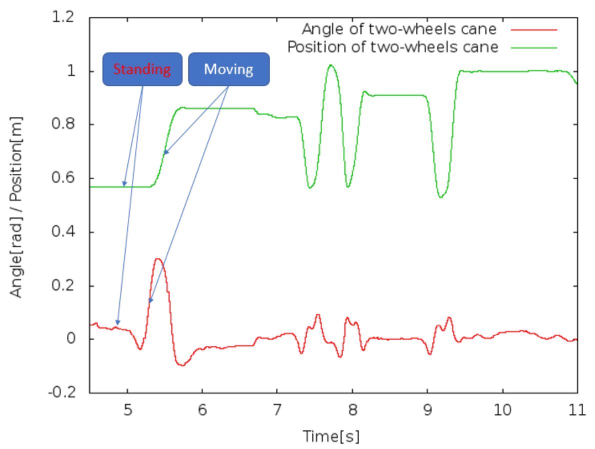

Fig. 6. Angle and position of two-wheel cane when it help users maintain balancing.

We present two cases: the first case is when users need to remain stable at the stand upright position (Fig. 7), at that time the two-wheel cane helps users achieve the balancing point through the handle; the second case is when the cane supports users to move (Fig. 8). In this case, the two-wheel cane is based on the angle of the rod compared to the stability point to get to a suitable position to support users.

Fig. 7. Two-wheel cane helps users to stand.

Fig. 8 shows that when the user needs to go ahead, the cane is tilted at an angle of ϕ compared to the vertical axis. Then, an output torque is applied to the motor axis, this torque calculated by (9) helps the two-wheel cane change the position with the corresponding angle of θ.

The results are shown in Fig. 6, with the angle of ϕ changes from 0 rad to around 0.3 rad, the two-wheel cane automatically changes its position from around 0.58 m to 0.88 m before achieving a balancing point to help users stand from the sixth second.

Fig. 8. Two-wheel cane help users to move.

V. Conclusion and Future Work

We designed the hardware of the two-wheel cane based on a natural rubber tire electric wheel with a high-speed processing controller for walking assistance. From the experimental results on the hardware, the two-wheel cane is more effective to help the users to maintain balance. In future work, we intend to reduce the size of the system while increasing capacity of the battery to increase the running time of the two-wheel cane without charging. Moreover, we will test the two-wheel cane at the rehabilitation center to get more experimental results and improve it.

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