Dynamic Modelling and Analysis of a Cane under Cane Gait

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Abstract—In order to develop a cane robot to be compliant with the motion habits of an elder during his walking assisted by a general cane, the motion state of an ordinary cane was analysed in this paper. Two different cane-assisted gaits were introduced and the motion state of the cane was divided by two motion phases. The relationship of the human-cane interaction force for each phase was analysed, and the dynamic model of the cane was founded individually. An experimental setup was constructed and validity of the proposed dynamic models were verified.

Index Terms—dynamic model, cane gait, walking habit

I. INTRODUCTION

Due to the aging society, disabled and semi-disabled elderly increase rapidly [1]. In 2015, the population over the age of 60 will grow from 11% to 12% to more than 25% in Asia [2]. How to solve the daily care of the elderly with a modern way is a work for researchers in the field of robots always working on. Currently, there are three kinds of robots assisting walker’s function, namely the exoskeleton robot, the walking frame robot and the cane robot.

Currently, a lot of research focusing on the exoskeleton robot have been done by many scholars [3]-[6]. For example, Yoshiyuki Sankai developed an exoskeleton robot called HAL-5. The robot can help the elderly complete some action, such as walking and stairs up and down [7]-[9]. However, exoskeleton robots still have some drawbacks, such as the robot was connected with user by bundling. It causes the user’s body will produce poor blood circulation and it is too unachievable for an elderly to wear the equipment independently. For the research on walking aid robot, a walking robot JARoW [10], [11] was proposed, in which a laser sensor was employed to locate the relative position of legs and the center of the walker. The robot was controlled to coincide COGs of users and the robot frame. Walk frame robots are usually with large size and restrict human motion, and it is not suitable for indoor environment.

Generally, certain motion abilities were survived for most of elderly people, the most effective walking assist equipment for them is something with smaller size and easy to use and unrestricted moving just like a general cane. Cane robots just meet the requirements mentioned above. In 2013, Toshio Fukuda developed an omnidirectional cane robot based on human walking intention. The robot recognized the intention of the direction by analyzing the interaction between man and the robot was realized to assist users walking effectively [12]-[16]. However, there are still some problems with this kind of robots. For example, the supporting stick and the moving platform are always integrated and there is no any joint connecting them together. The stick is perpendicular with floor and there is no effective support comparing with that of a general cane. Moreover, it is incompliant with the motion habits of an elder walking assisted with a cane.

In this paper, In order to develop a cane robot to be compliant with the motion habits of an elderly people during his walking assisted by a general cane, the motion state of an ordinary cane was analyzed firstly, and then two different cane-assisted gaits were introduced and the motion state of the cane was divided by two motion phases. The relationship of the human-cane interaction force for each phase was analyzed, and the dynamic model of the cane was founded individually. An experimental setup was constructed and validity of the proposed dynamic models was verified.

II. ANALYSIS OF CANE’S MOTION STATE

There are two kinds of cane gait, one is Two-point gait and the other is the Three-point gait. The Two-point gait is shown in Fig. 1(a). In this situation, a cane is on the same side with the unaffected extremity. On first step, the cane and affected extremity are stepped out simultaneously, and then the user holds the cane and supports body weight with arm power and step out the unaffected extremity after the body is stable. In the Three-point gait, as shown in Fig. 1(b), a cane is also required on the same side with an unaffected extremity before walking. At first, the user steps out the cane and then holds the cane tightly supporting his body with the arm power, then the affected extremity is stepped out when his body is stable. After that, the unaffected extremity is stepped out.

The cane motion can be divided into supporting phase and non-support phase. In the supporting phase, the cane provides support force to stabilize the body, referring to step2 in Two-point gait, and step3 in Three-point gait. In non-support phase, the cane move forward after the body is stable, which refers to step1 in Two-point gait and refers to step1 and 2 in Three-point gait.
III. DYNAMICS MODELS OF CANE

A. Establishment of Coordinate System

In order to accurately explain the movement state of cane under cane gait, defining the earth coordinate system and the cane coordinates as follows:

![Figure 2](image)

As shown in Fig. 2, \(O_0 - x_0y_0z_0\) is the earth coordinate system, \(y_0\) is point toward the Geographic North Pole; \(x_0\) is perpendicular to \(y_0\) and point to the East; \(z_0\) is perpendicular to the plane \(x_0y_0z_0\).

\(O_1 - x_1y_1z_1\) is the cane coordinate system, \(x_1\) is perpendicular to \(y_1\) and point to right; \(y_1\) is the forward direction of cane along the handle.

![Figure 3](image)

Under these two coordinate systems, according to the analysis of Section II, we also divide the motion state of the cane into two phases, namely the Support phase and the Non-support phase. The support phase is defined as the cane’s terminal remains stationary and cane provide support force, as shown in Fig. 3(a).

The Non-support phase was defined as the cane’s terminal was hung up and moved from one point to another point as shown in Fig. 3(b).

The state cane does not provide support force. During Non-support phase, the cane motion is combined rotation around the handle and translation together. In support phase, the human force, the gravity and the supporting force from floor are simultaneously acted to determine the cane motion. In non-support phase, only the human force and the gravity are acted simultaneously to determine the cane motion. The acceleration in the direction of \(y_1\) axis was defined as \(a_{y_1}\),

\[ a_{y_1} = S \times a_{y_1} + C \times a_{y_2} \]

\[ S = \begin{cases} 1 & F_z \geq 0 \\ 0 & F_z < 0 \end{cases} \]

\[ C = \begin{cases} 0 & F_z \geq 0 \\ 1 & F_z < 0 \end{cases} \]

where \(a_{y_1}\) and \(a_{y_2}\) represent acceleration of support phase and the non-support phase respectively.

B. Dynamic Model in Support Phase

In this section, the acceleration of the cane on \(Y\) axis is analysed in \(O_1 - x_1y_1z_1\) coordinate system during supporting phase. Illustration of the acceleration decomposition of the cane is shown in Fig. 4.

![Figure 4](image)

In support phase, the cane rotates around the other end of the cane. This movement causes the cane’s terminal to be almost static. Therefore, the acceleration in \(y_1\) axis is mainly the component of the gravity acceleration without gravity compensation. The acceleration produced by other forces at \(y_1\) axis is approximately zero, so

\[ a_{\text{Sup}} = mgsin\theta = a_{y_1} \] (2)

C. Dynamic Model of Swing in Non-support Phase

In this section we analysed acceleration of the cane on \(Y\) axis caused by swing motion. In \(O_1 - x_1y_1z_1\) coordinate system, the torque exerted on cane by human and the gravity act simultaneously to determine the swing motion of the cane. The movement of cane is divided into three stages.

\(F_h\) is force exerted on cane by human. \(T\) is torque exerted on cane by human composed of \(F_1\) and \(F_2\),

\[ T = F_1 \times l_1 + F_2 \times l_2 \]

When cane are perpendicular to the ground and still static, we record the status as state 1 as shown in Fig. 5(a). When the torque \(T\) causes the cane to do counterclockwise motion, we record the status as state 2 as shown in Fig. 5(b). When the torque \(T\) and
gravity cause the rotate motion of cane together, we record the status as state3 as shown in Fig. 5(c). The movement of cane change between the three states. We get the formula for swing motion

\[ T - mg \sin \theta \cdot d = J \ddot{\theta} \]  

(3)

where \( m \) represents quality of lower part, which consists of F/T senor and the lower part of cane. \( d \) represents the distance from the rotation point to COG of the lower part. \( \theta \) represents the angle between \( z_0 \) and \( z_1 \). \( J \) represents the moment of inertia of cane, get the formula

\[ \ddot{\theta} = \frac{a_{\text{Rota}}}{l} \]  

(4)

where \( a_{\text{Rota}} \) represents the linear acceleration of the cane’s terminal, \( l \) represents length of cane. We see the cane as a uniform thin rod and add a coefficient \( k \) to make up the error of the moment of inertia.

\[ J = \frac{1}{3} \cdot m \cdot l^2 \cdot k \]  

(5)

The coefficients \( k \) are empirical values. We get a formula for calculating moment of inertia of a cane as formula(5), the linear acceleration of the cane’s terminal can be obtained, get the formula

\[ a_{\text{Rota}} = \frac{3(T - mg \sin \theta \cdot d)}{mlk} \]  

(6)

D. Dynamic Model of Swing in Non-support Phase

In this section we analysed acceleration of the cane on Y axis caused by translation motion as shown in Fig. 6.

\[ a_{\text{Trans}} = \frac{(F_{\text{Horz}} \cos \theta + F_{\text{Vert}} \sin \theta)}{m} \]  

(7)

When the translation speed of lower part and upper part of the cane is synchronized on the \( z_1 y_1 \) surface, Interaction force between them don’t appear. When the speed is not synchronized, interaction force between them will appear. Horizontal force called \( F_{\text{Horz}} \), the vertical force \( F_{\text{Vert}} \). The acceleration produced by the translation on the Y axis is \( a_{\text{Trans}} \).

\[ a_{\text{Trans}} = a_{\text{Rot}} + a_{\text{Trans}} = ay_2 \]  

(8)

IV. EXPERIMENT

A. Experiment Setup

In order to verify validity of the proposed model, a cane motion monitor system was designed. A F/T sensor and a gyro sensor were mounted on the cane as shown in Fig. 7.

The experimental platform parameters are as follows: the quality of the lower part is 0.75kg and the length of cane is 0.87m, the distance from rotation point to COG of lower part is 0.5m. In earth coordinate system \( O_0 x_0 y_0 z_0 \) we choose a path called \( \text{Route} \), as shown in Fig. 5. \( \alpha \) is the plane containing the Route and the \( z_0 \). The plane \( z_1 O_1 y_1 \) coincides with the plane \( \alpha \).

The cane is pitched in the plane \( \alpha \). An user walked with Three-point gait use cane motion monitor system along the \( \text{Route} \) with 0.16m/s. Recording the force data from the F/T sensor and the posture and acceleration.
information from the gyro. The force of the cane includes the force along the $z_2$ axis, denoted as $F_z$, and the torque around the $x_1$ axis, denoted as $T_x$. These two parameters reflect force situation of cane. The cane posture is reflected by the pitch angle of the cane in a plane, denoted as Pitch. The cane’s terminal acceleration on the $y_1$ axis is denoted as Acc, the parameter reflect the movement of the cane.

![Figure 8. Experimental method description](image)

**B. Data Analysis**

In Fig. 9, the blue line represents $F_z$ (N), the green curve represents Pitch (unit: degree); the red curve represents Acc (unit: m/s²); the light blue curve represents $T_x$ (unit: N·M). The black curve is zero reference line.

![Figure 9. Variation of force, moment, angle and acceleration](image)

It can be seen from the curve that the four parameters $F_z$, Pitch, $T_x$ and Acc are cyclically changed. This characteristic is consistent with the characteristics of gait changes when a person uses a cane.

Inputting real measurements of $F_z$, Pitch and $T_x$ into formulas and setting $k$ as 1.3, then the acceleration of cane’s terminal on $y_1$ axis is shown in Fig. 10. The blue and the green curves represent the acceleration measured by gyro and calculated based on the dynamic model respectively. It can be seen that the two curves match very well. The results verified the dynamic model of a cane under cane gait is correct.

![Figure 10. Variation of acceleration in Y axis](image)

**V. CONCLUSION**

In this paper, two different cane-assisted gaits were introduced and the motion state of a general cane was divided by two motion phases. The dynamic models of the cane were founded individually and an experimental setup was constructed and validity of the proposed dynamic models were verified. The results of this paper are good for developing a cane robot to be compliant with the motion habits of an elder during assisted by a general cane.

**REFERENCES**


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