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Development of a Line-Walking Mechanism for Power Transmission Line Inspection Purpose

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***Abstract*—A mobile mechanism with biped configuration is proposed for power transmission line inspection purpose. The wire-walking cycle of the designed mechanism composed of single-support phase and double-support phase. During the process of single-support phase, one foot hang on line and the other foot swing from rear to front to overcome obstacles on line and realize wire-walking locomotion. The novel mechanism designing enable the centroid of the robot concentrate on the hip joint to minimize the drive toque of hip joint and keep the robot stable during the single-support phase. And the centroid of the robot will be adjusted to concentrate to the other leg to start a new single-support phase. Both the forward kinematics model and inverse kinematics model are established in this paper for motion control. The feasibility of this concept is then confirmed by designing a real wire-walking robot and by performing experiment with a simulated line environment.**

I. INTRODUCTION

THE purpose of inspection tasks for power transmission line is to check running state and find damages of high voltage power transmission lines equipments. So far, there are two methods for checking power transmission lines. One method is that power transmission line equipments have been checked manually by a worker with a telescope on the ground. These working methods have many disadvantages, such as long inspection cycles, high working intensity and high danger. And it is difficult to assure the checking quality especially in mountain areas, grasslands and aboriginal forests because of severe environments. Another method is that power transmission line equipments have been inspected by helicopters or air planes with checking devices. Despite the advantages of higher efficiency, the disadvantage of this method is that it is higher expenditure and poor checking quality in bad climate.

Since the end of 1980s, many researchers have investigated in developing inspection robots to assist human tasks or to work in place of humans in power transmission line site. A robot applying to inspection of the 66KV fiber-optic overhead ground wires (OPGW) is described in [1], which can run on the OPGW and navigate such obstacles as counterweights and clamps. In [2], a new type of mobile robot mechanism is described, which is composed of dual arms, 4 sets of actuators and crawlers. The experiment results prove that the robot can run on the overhead ground wire and navigate the tower obstacles. A robot consisting of multi-unit modules is reported in [3]. It can run and navigate obstacles on telephone wires and power transmission lines. Because it has 18 DOF, the power-consumption of the robot is too high to apply in practice. Many other types of inspection robot prototypes are introduced in [4], [5], [6].

Due to it is easy to control and sample configuration, mechanism with two arms (legs) is widely used in power transmission line inspection robot design. During the process of obstacle-navigation, inspection robots with two arms need hang on the power line with one arm, thus the other arm can be controlled to pass over the obstacle. In order to keep the robot at a desired pose during the obstacle-navigation process, a mechanism with powerful grippers was introduced in []. With the gripper the robot can be fastening on the wire to resist the effect of gravity. But the disadvantages of this mechanism are that due to the gravity acting the joints need to be driven by high-torque power motors and the clamping fore may damage the power line. In [7] robot with additional centroid adjustment mechanism was introduced, when the robot negotiate obstacles on lines the centre of mass is adjusted to the arm which is hang on the lines to keep the horizon pose of the body and protect lines against the gripping forces. The disadvantage of this mechanism is that the additional drive system for centroid adjustment increase the complexity of the robot and the process of the obstacle-navigation is time-consuming.

This paper describes a novel biped mechanism for power transmission line inspection purpose. This paper is organized as follows: section 2 describes the mechanism of the biped robot and its walking cycle; section 3 describes the kinematics of the robot; section 4 the prototype of the biped robot was introduce and experiment was shows in section 5; finally is the conclusion in section 6.

II. MECHANICAL STRUCTURE

The purpose of the line-walking robot is semi-autonomous reconnaissance in confined environments of power transmission line. The robot will be deployed on overhead ground wire or overhead live wire of power transmission system. The robot must be sufficiently flexible in order that it can traverse horizontal and inclined wire and overcome tower obstacles on wires such as counterweight and clamps in order to provide video surveillance of power transmission line

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system as large range as possible. For effective and prolonged operation and minimal wire damage, the line-walking robot needs to be small in size, light in weight and consume as less power as possible.

A. Description of Mechanism

The line-walking mechanism is designed based on biped structure and it is supported by two feet which can hold on lines. Both of the feet can be put on or put off line by the joint motion of the robot and with the alternative hand movement the robot can realize line-walking locomotion. The biped robot consist of 7 DOF such as 2 DOF in each ankle, 1 DOF in each leg and 1 DOF in waist. Both of the feet can be put on or put off line by the joint motion of the robot, and with the alternative foot movement the robot can realize line-walking locomotion. The robot has two prismatic joints to adjust the length of the length of the two legs respectively, and the centroid of the robot can be adjusted to the leg hang on lines during the single-support phase, thus the robot can realize stable walking locomotion reliable.

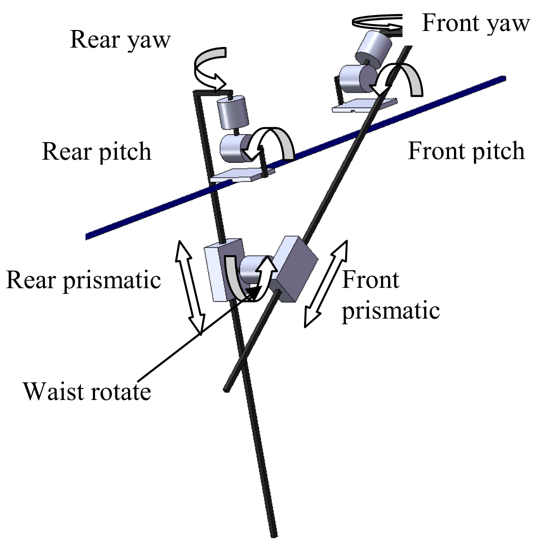


Figure .1 Concept of the biped wire-walking robot

The mechanism of the wire-walking robot is show in Figure1. The robot composed of three segments: feet, legs and waist. Each leg of this robot is composed of one pitch joint, one yaw joint and one prismatic joint. Pitch joint and roll joint providing steering capability of the feet relative to leg, and by adjusting angles of the joints adapt the feet to the orientation of wire. The prismatic joints allow the robot expending or contracting its legs, and adjusting the CoM position of legs respect to waist joint at the same time. The slide blocks of the two legs were connected by a rotation joint-the waist articulation and the angle of this joint together with the length of the two legs determines the gait of the robot.

B. Walking Cycle

The main way in which walking locomotion is implemented in line-walking robot is based on so-called static walking. From the definition of walking, we see that at least one foot is always on the line. If we now construct a fully actuated robot, and ensure (by means of active control) that the CoM (central of mass) is always locate at the leg that hang on line, then if the robot moving slowly enough (hence the name static), it is always stable. If we then command the joints to move periodically such that the rear foot lifted, moved forward, and put down, then we obtain a stable walking motion.

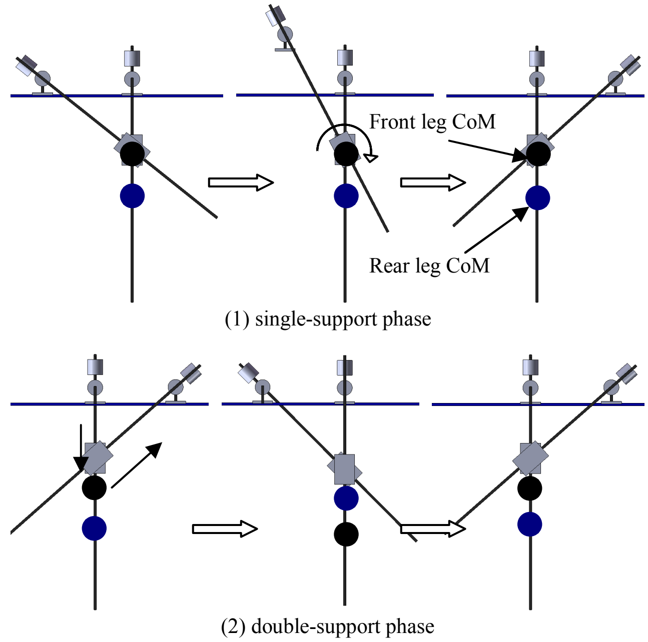
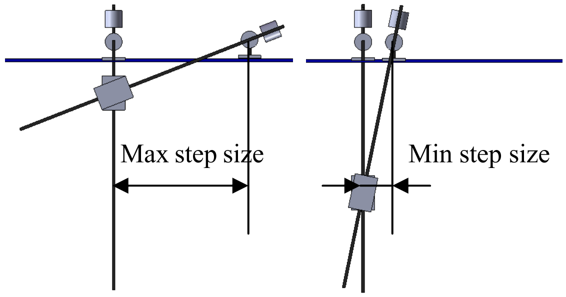


Figure .2 Walking cycle of wire-walking robot

A walking cycle is composed of two phases: a double-support and a single-support phase. While both of the feet are on the line during the double-support phase, only one foot is stationary on the line in the single-support phase while the other feet swing from the rear to the front. During the double-support phase the robot's CoM (central of mass) in the static case must be transferred from the rear leg to the front leg.

The walking cycle and the according joint displacement of the robot are shown in Figure 2. As shown in figure .2.1, during the process of single-support phase, the centroid of swinging leg was adjusted to coincide with the position of waist joint by the motion of its prismatic joint; then with the rotation of the waist joint, the swinging leg swing from rear to front till the foot contact the line. In process of double-support phase, centroid was adjusted from rear leg to front leg by the motion of the two prismatic joints as shown in Figure 2.1. If both the foot and the waist trajectories are known, all joint trajectories of the wire-walking robot can be obtained by the kinematics constraints.

The step size of line-walking robot is determined by the length of the leg hang on line as shown in Figure 3. During the single support phase the swing leg's length is set to a constant to make sure the mass of the leg is located at the waist joint. As shown in figure 3.1, when the prismatic joint of rear leg contract to the minimal length the robot can get the maximum step size. And vice versa, when the rear leg extended to the maximum length the robot get the minimum step size. Thus according to the dimension of obstacles we can adjust the step size easily.



(1) maximum step size (2) minimal step size

Figure .3 step size adjustment of the wire-walking robot

III. KINEMATICS MODEL

Here, we utilize Denavi-Hartenberg model for displacement analysis of line-walking robot. Coordinate system representation for line-walking robot is shown in Figure 1.3.

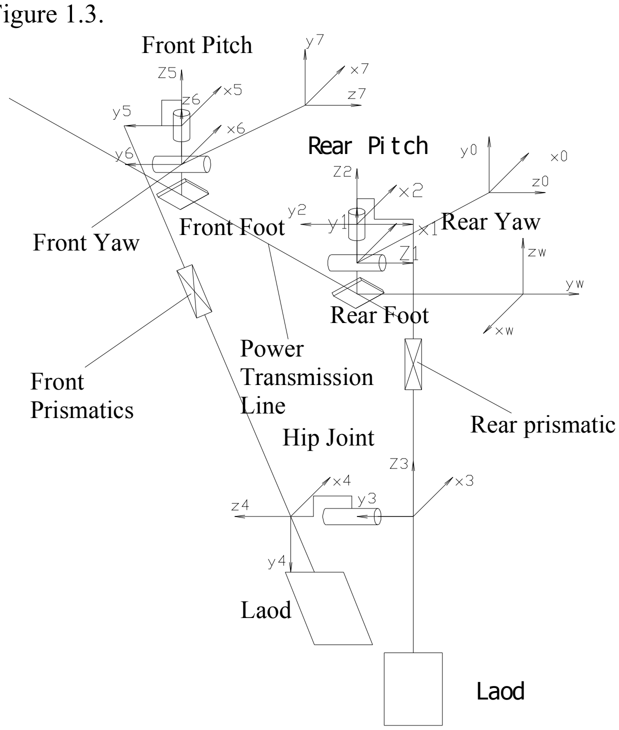


Figure .3Walking cycle of wire-walking robot

A. Forward Kinematics Model

Since the robot is symmetrical, it is realizable to consider the kinematics in the same phase. The coordinate frames are assigned in the three dimension space as single-supporting phase and the base coordinate frame is attached to the rear foot which is anchored on the wire. The follows Table 1 is the link DH parameters during the single-support phase (rear foot on line).

Table 1: Link DH parameter (rear foot on line)

Motion joint	a_{i-1}	α_{i-1}	d_i	θ_i
Rear pitch	0	0°	0	$\theta 1$
Rear Yaw	0	90°	0	$\theta 2$
Rear Prismatic	0	0°	$-d3$	0
Hip rotation	0	90°	0	$\theta 4$
Front Prismatic	0	−90°	$d5$	0
Front Yaw	0	0°	0	$\theta 6$
Front Pitch	0	−90°	0	$\theta 7$

During single-support phase, the mechanism of the wire-walking robot forms an open kinematics chain. And the final robot transformation matrix can be written as:

$$ {}^0_7T = \begin{bmatrix} n & s & a & p \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. $$

The forward kinematics of the robot is derived in the equation sets as follows:

$$ n_x = ((c_1c_2c_4 + s_1s_4)c_6 - c_1s_2s_6)c_7 + (c_1c_2s_4 - s_1c_4)s_7 $$
$$ s_x = (c_1c_2s_4 - s_1c_4)c_7 - ((c_1c_2c_4 + s_1s_4)c_6 - c_1s_2s_6)s_7 $$
$$ a_x = (-c_1c_2c_4 - s_1s_4)s_6 - c_1s_2c_6 $$
$$ p_x = (-c_1c_2s_4 + s_1c_4)d_5 - s_1d_3 $$
$$ n_y = (s_1c_2s_4 + c_1c_4)s_7 - ((s_1c_2c_4 - c_1s_4)c_6 - s_1s_2s_6)c_7 $$
$$ s_y = (s_1c_2s_4 + c_1c_4)c_7 - ((s_1c_2c_4 - c_1s_4)c_6 - s_1s_2s_6)s_7 $$
$$ a_y = (-s_1c_2c_4 + c_1s_4)s_6 - s_1s_2c_6 $$
$$ p_y = (-s_1c_2s_4 - c_1c_4)d_5 + c_1d_3 $$
$$ n_z = (s_2c_4c_6 + c_2s_6)c_7 + s_2s_4s_7 $$
$$ s_z = -(s_2c_4c_6 + c_2s_6)s_7 + s_2s_4c_7 $$
$$ a_z = -s_2c_4s_6 + c_2c_6 $$
$$ p_z = -s_2s_4d_5 $$

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The double-support phase inverse kinematics can be determined similarly.

B. Inverse Kinematics Model of Single-support Phase

During the single-support phase, in order that the CoM of the robot is inside the supporting-foot area, the rear pitch joint is adjusted according to the inclination of the wire to make the rear prismatic joint move in along the vertical direction. And the front prismatic joint is adjusted to a proper position to make sure that the CoM of front leg located at the axe of the hip joint. Then given a desired foot location, the single-support phase inverse kinematics is thus determined by:

$$\begin{aligned}
&\theta_1 = 0 \\
&\theta_2 = \arctan(p_z / p_x) \\
&d_3 = p_y + \cos\theta_4 d_5 \\
&\theta_4 = \arcsin(-p_z / d_5 \sin\theta_2) \\
&d_5 = const \\
&\theta_6 = \arcsin((a_x \sin\theta_1 - a_y \cos\theta_1)/\sin\theta_4) \\
&\theta_7 = \arcsin\left(\frac{s_2 n_z - (s_2 c_4 c_6 + c_2 s_6) s_z}{s_2^2 s_4^2 + (s_2 c_4 c_6 + c_2 s_6)^2}\right)
\end{aligned} \quad .$$

C. *Inverse Kinematics Model of Double-Ssupport Phase*

The double-support phase inverse kinematics can be determined similarly. During double-support phase both foot have wire contact, thus form a planar five-bar mechanism with two DOFs as shown in Figure .5. To avoid gravity acting as possible as can be, the trajectory of CoM was setting to parallel to the wire. Since it is difficult to get the real position of CoM, here the displacement of waist joint x was used to take the place of CoM for they are approximately equal .

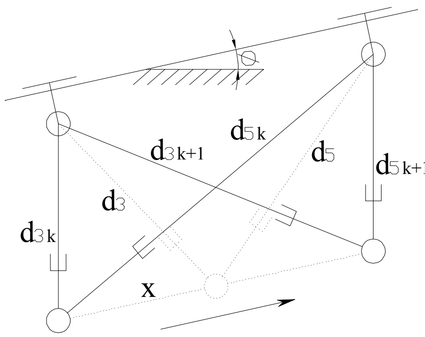


Figure .5 double-support phase

As shown in Figure .5, by solve the triangle form equation we can get the joint displacement of d_3, θ_4 and d_5 as follows:

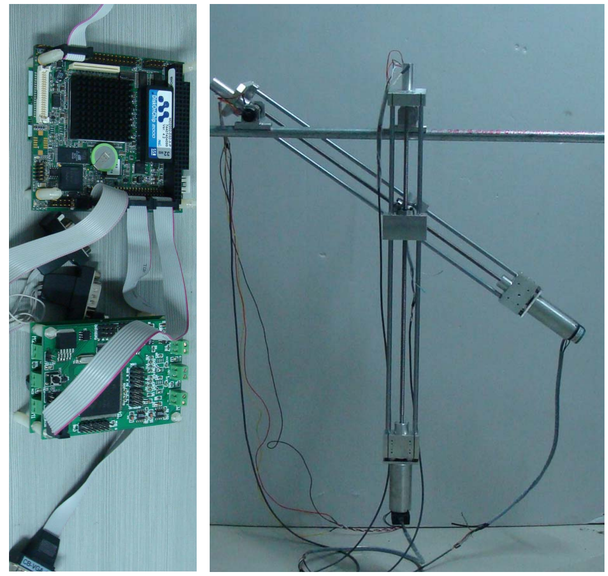
$$\begin{aligned}
&d_3 = \sqrt{d_{3k}^2 + x^2 - 2x d_{3k} \sin\varphi} \\
&\theta_4 = \arccos((d_3^2 + d_5^2 - l^2)/2 d_3 d_5) \\
&d_5 = \sqrt{d_{5k}^2 + (l-x)^2 + 2(l-x) d_{5k+1} \sin\varphi}
\end{aligned} \quad .$$

With the forward kinematics equation we can get the other joints' displacement as follows:

$$\begin{aligned}
&\theta_1 = \arcsin((p_x(c_4 d_5 - d_3) - p_y c_2 s_4)/(c_2^2 s_4^2 d_5 - (c_4 d_5 - d_3)^2)) \\
&\theta_2 = -\arcsin(p_z / s_4 d_5) \\
&\theta_6 = \arcsin((a_x \sin\theta_1 - a_y \cos\theta_1)/\sin\theta_4) \\
&\theta_7 = \arcsin\left(\frac{s_2 n_z - (s_2 c_4 c_6 + c_2 s_6) s_z}{s_2^2 s_4^2 + (s_2 c_4 c_6 + c_2 s_6)^2}\right)
\end{aligned}$$

IV. EXPERIMENTS

An experimental setup is introduced to confirm the feasibility of our concept.



(1) Controller and diver (2) line-walking mechanism

Figure .6 Realized line-walking robot

A. *Realized Device*

The design that shows the configuration of the line-walking robot is shown in Figure .6. The robot consists of identical pairs of legs, feet and a waist. All the rotation DOFs of the robot are realized by a combination of DC motor, thrust and radial bearings. Combination of DC servo motor and ball screw were chosen for the prismatic joint and the advantage of this combination is that it has no coupling and it is backlash free. The dimension of the prototype robot is approximately 800mm in height and 100mm in width when all the joints are in the zero position. The maximum length of the tower obstacles that the robot can overcome is 300mm, and the minimum cross angle of the suspension angle tower is 120 degree.

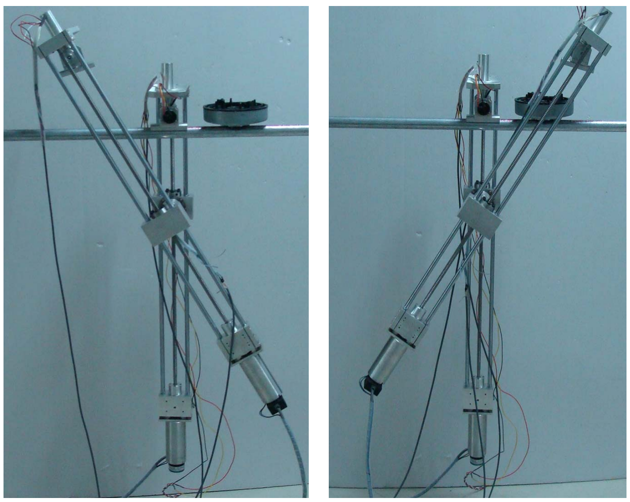
When the robot actually walking on line during double-support phase, due to the closed chain form there may be interface of the joint which will cause energy consume because of the errors of its calibration. The foot joints (pitch and yaw joint) and the hip joint is designed to be highly complaint in order to ensure robustness against modeling errors. Which means during the process of double-support phase the wire-walking robot might rotate around any of the foot boundaries due to external disturbance (considered equivalent to a passive DOF).

B. *Control & Software*

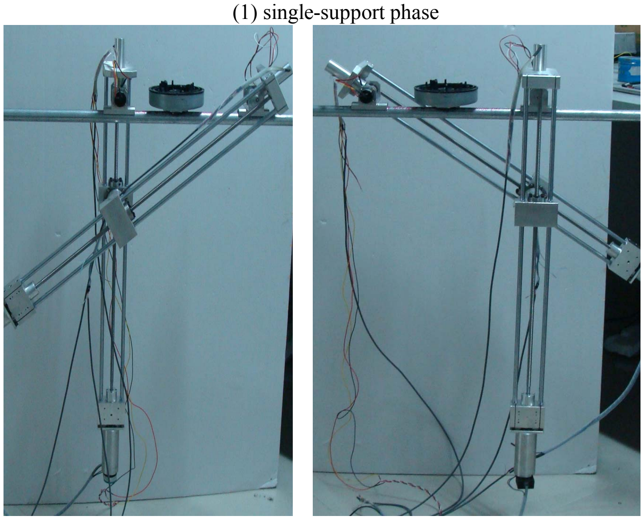
The biped wire-walking robot is controlled by SCM/SPT2F, a miniaturized modular PC/AT compatible CPU board with 6 serial ports to communicate with the host computer and sent motion command to the servo driver modular. Its operating system is a RT-Linux that enable the execution of real time processor. The feature of RT-Linux is essential for the identical controller of robot systems. The control software of the wire-walking robot has two modules. One modular is used to communicate to the host computer and sent motion command to the servo driver and the other module is used to carry out the computations based on the kinematics equation to control the joints' trajectories to realize wire-walking locomotion.

The driver modular is based on the TMS320F2812 digital signal processor chip from TI, for its support multi-motor control, low power consumption and its high speed performance. Each DSP controller has two build in quadrature encoder pulse (QEP) circuits to read the encoder of servomotor, thus with each chip, two motors can be controlled with encoder feedback. The total servo motor number of the wire-walking robot is 7, which means at least 4 driver modular are needed. The control program is written in C language and the servo rate is 1Hz.

C. Experiments



(1) single-support phase

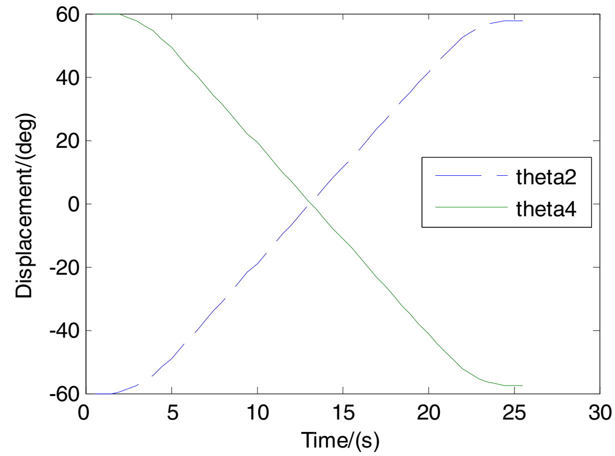


(2) double-support phase

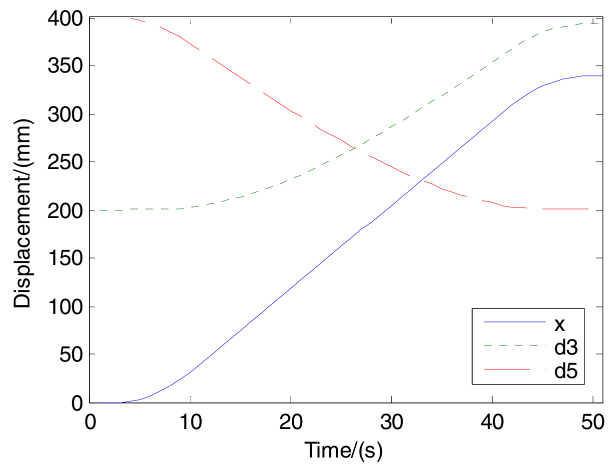
Figure.7 Pictures of line-walking Experiments

Static walking experiments were conducted to verify the mechanism of the biped wire-walking robot that was developed in this study. According to the actual situation, the real power transmission line can be seen inflexible due to large tension act on it. Thus a rigid stick was selected to simulate the real power transmission lines.

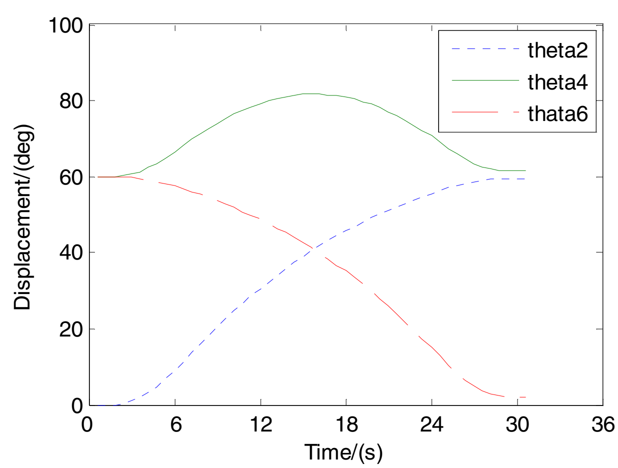
As shown in Figure .7, the line walking robot was hung on the simulation line, and the experiments were executed in two steps: firstly, the CoM of the robot was located at the hanging leg and the swinging leg swung from rear to front to overcome obstacles on line, then the CoM of the robot was adjusted to the front leg to start another swinging locomotion. The joints' displacement of during the line-walking locomotion is shown in Figure .8.



(1)Joints (θ_2 , θ_4) displacement during single-suppot phase



(2)Joints (x , d_3 , d_5)displacement during single-suppot phase



(3)Joints (θ_2 , θ_4 , θ_6) displacement during single-suppot phase

Figure.8 Pictures of line-walking Experiments

V. CONCLUSION

A biped mechanism, which is able to apply the designing of power transmission line inspection robot, is proposed in this paper. Like biped robot for ground motion, walking of wire-walking robot is a periodic phenomena. A walking cycle is composed of two phases: a double-support and a single-support phase. While both of the feet are on the wire during the double-support phase, only one foot is stationary on the wire in the single-support phase while the other feet swing from the rear to the front. The novel mechanism designing enable the centroid of the robot concentrate on the hip joint to minimize the drive toque of hip joint and keep the robot stable during the single-support phase. After analysis of the walking cycle of mechanism, the forward and inverse kinematics equations were proposed for trajectories generation. A prototype of power transmission line inspection robot was developed based on this mechanism and experiments shown the validity.

Wheel dive mechanism will be installed to the robot feet in the future to achieve higher moving speed when there are no obstacles on line.

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