Dual Arms Running Control Method of Inspection Robot Based on Obliquitous Sensor

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Abstract - Inspection robot with dual wheels encounters upslope and down slope, when it runs on the overhead ground wires (OGWs) which displays catenary shape. The tilt of the body of inspection robot, which is caused by the angle variation of catenary in different position, will occur during running procedure, and disenable to check vertically the transmission lines by camera. An adjustment method, which can keep the body of inspection robot in horizontal pose, is presented by the obliquitous sensor changing the length of the manipulators in this paper. In order to implement the pose adjustment, the dynamic model is established by Lagrange method. Finally, the simulation and experiment results show that the adjustment method proposed is feasible.

Index Terms - dual arm running; obliquitous sensor; inspection of transmission lines; mobile robot

I. INTRODUCTION

The purpose of inspection tasks for power transmission lines is to check running state and find damages of extra-high voltage (EHV) power transmission lines equipment. Obviously, inspection tasks are very important for normal operation of power transmission lines. So far, there are two methods for checking power transmission lines. One method is that power transmission line equipment has been checked manually by workers with a telescope on the ground. Sometimes, they have to climb the metallic towers or ride in gondolas suspended on the overhead ground wires. These working modes have many disadvantages, such as long inspection cycle, high working intensity, huge expense and high danger. It is difficult to assure the checking quality in mountain areas, grasslands and aboriginal forests because of severe environments. Another method is that power transmission line equipment has been inspected by helicopter with the checking devices which are thermal infrared imager, visible light camera and so on. The advantage of helicopter is higher efficiency for checking, ad hoc for high altitude, high and cold zone, and no mans land. The disadvantage is higher expenditure and poor checking quality in bad climate.

The inspection robot can take place of workers to complete inspection tasks under 500KV EHV power transmission lines environment. The research on the inspection robot is started from the end of 1980s. A robot applying to inspection of the 66KV fiber-optic overhead ground wires (OPGW) is described by Tokyo electric power Co. Inc. 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 by Mitsubishi motor business corporation, which is composed of dual arms, 4 sets of actuators and crawlers. The experiment results prove that the robot can run on the OGWs and navigate the metallic 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 [4-6]. Except for research mentioned above, the other technique has been investigated for EHV in [7-11]. In recent years, key technology on inspection robot for EHV had been researched in [12-13]. Because there are so many problems on obstacle-navigation so that all the above robots haven’t been applied for real power transmission lines until the present. One of the main reasons is that the design of autonomously navigable mechanism is very difficult. However, the research work for the type of robot is still on the way.

This paper describes that Inspection robot encounters upslope and down-slope, when dual wheels run on the OGWs which displays catenary’s shape. The tilt of inspection robot’s body is happened because the contact point between the running wheels and OGWs is variational with the catenary’s angle variation in different position during dual wheels running procedure. Above problem will disenable to check vertically the power transmission lines by camera for inspection robot. A pose adjustment method, which can keep robot body’s horizontal pose, is presented by the obliquitous sensor changing the length of manipulators in this paper. In order to implement pose adjustment, the dynamic model of pose adjustment mechanism is established by Lagrange method. Finally, the simulation and experiment results show that the pose adjustment method proposed is feasible.

This paper is organized into five sections. The following section, section 2, introduces inspection robot configuration. Section 3, describes pose adjustment principle. Section 4, establishes the dynamic model of the pose adjustment mechanism and carry through the simulation test and experiments in real environment. The last section of this paper
II. Configuration of Inspection Robot

The main obstacles on the OGWs are counterweights, clamps and towers. In power transmission system, the line arrangement and the structure size of obstacles are approximate for the towers that are the same style on a power transmission lines. Power department can provide the structure data information of obstacles. Inspection robot can run and navigate obstacles on OGWs autonomously. Equipped with cameras, the robot can detect the damages of power transmission lines equipment. The data and images detected by the robot can be transmitted to the ground base station by the wireless transmission devices. The ground base station can not only receive, store and display the data and images but also complete real-time remote control and image processing simultaneously.

![Fig. 1. Inspection robot configuration](image)

Inspection robot configuration sees Fig. 1. \( \theta_1 \) is shift pair, its function is for centroid adjustment. The center of mass of inspection robot is concentrated into forearm or rear-arm by mass block drove in obstacle-navigation process. \( \theta_2 \) and \( \theta_3 \) are shift pairs, too. Their functions are to go up or down for forearm and rear-arm. When forearm or rear-arm is hung on the OGWs in obstacle-navigation process, the rear-arm or forearm is on or off the OGWs. \( \theta_3 \) and \( \theta_4 \) are revolving pairs. For example, when forearm is hung on the OGWs and the rear-arm has been off the OGWs, the body of inspection robot can rotate by the \( O_1/O_1 \) axis under the \( \theta_4 \) driving and implement to rotate obstacle-navigation. Especially, for breakthrough line, the behind wheel and clip can adapt the OGWs’ pose by interlock of \( \theta_3 \) and \( \theta_4 \).

When inspection robot is running on OGWs by two wheels, discharge impress, break strand lines and foreign material on the power transmission lines are observed by camera. If started, the body of inspection robot is adjusted to horizontal pose, the power transmission lines can be observed vertically by camera, sees Fig. 2. Because the OGWs display catenary’s shape, the angle with respect to horizontal plane is different in different position. As a whole, OGWs may be divided into two parts: upslope and down-slope. With inspection robot running ahead, the body of inspection robot will be tilted. The transmission power lines can not be observed vertically by camera due to the above causes mentioned, sees Fig. 2. Because the OGWs are away from the power transmission lines to over 9 meters, even the body of inspection robot has a small angle tilt, the offset will be bigger on the outside of 9 meters, the observed objectives run out the camera’s visual range.

Because the camera and the body of robot adopt rigid connection, the horizontal state of the body of robot can ensure that the power transmission lines are vertically observed only by adjustment the length of dual arms. At the same time, it can ensure approximately equal load to each wheel. Therefore, the control system becomes easy.

![Fig. 2. Inspection robot running on OGWs with two wheels](image)

III. Pose Adjustment Principle

In order to maintain the body of inspection robot to horizontal state, we can adjust the length of two arms and judge whether the body is horizontal or not according to zero output of the obliquitous sensor.

In order to avoid the electromagnetism disturbance in real environment, the obliquitous sensor is taken measures as follows,

1) The housing of the obliquitous sensor and the robot are equipotential.
2) The obliquitous sensor is shielded by copper and silicon steel sheets to avoid the influence of electromagnetism disturbance.
3) The output of the obliquitous sensor is average value after discarding those singularity values to avoid the influence of noise of the obliquitous and electromagnetism disturbance.
Assuming the length of dual arms is \(d_1\) and \(d_2\), respectively. The distance between forearm and rear-arm is \(d\), the included angle of the OGWs and the horizontal plane is \(\alpha\), and the included angle of body of inspection robot is \(\beta\). \(O_1, O_2\) are the rotary centre of the running wheel, respectively. \(P\) is the foot of a perpendicular. Obviously, \(O_1P = d\), sees Fig.3. The relation expression of \(d_1, d_2, d, \alpha\), and \(\beta\) is as follows,

\[
d_2 - d_1 = d \tan(\alpha - \beta) .
\]  

Fig.3 demonstrates the dual arms of inspection robot hung on the OGWs in down-slope state. When the body of inspection robot is horizontal pose, that is \(\beta = 0\). From Eq.1, we know that the difference of dual arms is as follows,

\[
d_2 - d_1 = d \tan \alpha .
\]  

If \(\beta \neq 0\), that is the output of the obliquitous sensor is not zero, the servo motors will adjust the length of dual arms until the difference of dual arms is satisfied Eq.2.

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IV. DYNAMIC MODEL OF POSE ADJUSTMENT

A. Dynamic Model

When inspection robot is running on the OGWs with single wheel, if the output of the obliquitous sensor equals zero, the body of inspection robot is horizontal state. If not, the body of obliquitous sensor is tilt. According to the positive-negative of output voltage of the obliquitous sensor, the tilt direction of the body is judged, and the mass block is moved by the servo motor, the pose of the body is adjusted, until the output voltage of the obliquitous is approximate zero.

In order to hold the horizontal pose of the body of inspection robot, we can adjust the length of arms. If the output of obliquitous sensor is zero, it tells us that the body pose is horizontal. According to the configuration of inspection robot, we choose to adjust the length of rear arm. Because of dynamic adjustment during the running process, the pose adjustment dynamic model is established as follows, sees Fig.4.

**Fig.3. Pose adjustment principle**

\[ P_1 = \left[ \sum_{i=1}^{3} l_i \cos \sum_{i=1}^{3} \varphi_i \right] \left[ \sum_{i=1}^{3} l_i \sin \sum_{i=1}^{3} \varphi_i \right] , \]  

\[ P_2 = P_1 + \frac{d_1 \cos \sum_{i=1}^{3} \varphi_i}{2} \sin \sum_{i=1}^{3} \varphi_i , \]  

\[ P_3 = \left[ \sum_{i=1}^{3} l_i \cos \sum_{i=1}^{3} \varphi_i \right] \left[ \sum_{i=1}^{3} l_i \sin \sum_{i=1}^{3} \varphi_i \right] , \]  

\[ P_4 = P_3 + \frac{d \cos \sum_{i=1}^{3} \varphi_i}{2} \sin \sum_{i=1}^{3} \varphi_i , \]  

\[ P_5 = \left[ \sum_{i=1}^{3} l_i \cos \sum_{i=1}^{3} \varphi_i \right] \left[ \sum_{i=1}^{3} l_i \sin \sum_{i=1}^{3} \varphi_i \right] , \]  

\[ P_6 = P_5 + \frac{d_2 \cos \sum_{i=1}^{3} \varphi_i}{2} \sin \sum_{i=1}^{3} \varphi_i . \]

In Eq.4 - Eq.8, \(l_1 = r_w\), \(l_2 = d_1\), \(l_3 = d\), \(\varphi_i (i=1,2,3,4)\) are included angles, sees Fig.5, their value shows the table 1.
Form the table, only the angle $\beta$ is variational during the length adjustment of the dual arms, therefore $\phi_i = 0$, $\phi_1 = 0$ ($i = 1, 3, 4$), $\phi_2 = -\beta$, $\phi_3 = -\beta$, $\phi_4 = -\pi$ , $\tilde{\phi}_1 = 0$, $\tilde{\phi}_4 = 0$ ($i = 1, 2, 3$).

Assumption the mass of arm is $m$, the mass of body of inspection robot is $M$, and taking into account $\phi_3 = \phi_4 = -\pi/2$, $\phi_3 + \phi_4 = -\pi$, the dynamic equation of the pose adjustment mechanism is established by Lagrange method as follows,

$$\tau_{d_1} = \frac{md_1^2 - 2md\ddot{\phi}_2 + 2md(d_1 - 0.5d_2)\ddot{\phi}_2^2}{4} + \frac{mg\sin(\phi_1 + \phi_2)}{2},$$

(9)

$$\tau_{\phi_2} = \frac{[md_1^2 + M d_3^2 + 4(M d_2^2 + md^2 + (d_1 - 0.5d_2)^2)]\ddot{\phi}_2}{4} - \frac{md_2}{2}d_2 - \frac{m(2d_2 - d_1)}{2}d_2\dot{\phi}_2 - \frac{[(3M + 2M)d_1 + 2M d_2]}{2}g\cos(\phi_1 + \phi_2) - \frac{(M + 2m)}{2}g\sin(\phi_1 + \phi_2).$$

(10)

B. Simulation Test and Experiment

The distance between one metallic tower and another tower, which hang the EHJV power transmission lines, is 400 to 500 metres. A period time is about 1000 seconds during down-slope and upslope path, when inspection robot spends about 15 minutes at a stride distance.

Because OGWs is shaped the catenary, the angle with respect to horizontal plane is different in different position, see Fig.5.

We define the angle is positive in down-slope path and the angle is negative in upslope path. Therefore, the variation orderliness angle of inclination of the OGWs may be approximate to cosine function. That is cosine function may be replaced variation of angle of inclination as the input of system. The input signal is denoted as follows,

$$B = B_0 \cos \omega t.$$  

(11)

In Eq.11, $B_0$ is the amplitude, $B_0 = 15^\circ$, $\omega$ is the circular frequency, $\omega = 2\pi / T$ Hz, $T$ is the period, $T = 1000$s.

The input curve sees Fig.6. The range of variation is from $15^\circ$ to $-15^\circ$. It reflects the angle of inclination of the overhead line in down-slope and upslope path when inspection robot is running on the overhead line with dual wheels.

![Fig.6. Input signal curve](image)

Assumption $X$ is the output vector of the system, denotes as follows,

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \phi_2 \\ \beta \end{bmatrix} = \begin{bmatrix} d_2 \\ \phi_2 \\ \beta \end{bmatrix}.$$  

(12)

$X_0$ is the initial state of the system, denotes as follows,

$$X_0 = \begin{bmatrix} d_{20} \\ \phi_{20} \\ \beta_0 \end{bmatrix} = \begin{bmatrix} 0.764m \\ 0^\circ \end{bmatrix}.$$  

Substitution the data of table I to Eq.9 and Eq.10, the dynamic model of pose adjustment mechanism can obtain during the down-slope and upslope path as follows,

$$\tau_{d_1} = \frac{md_1^2 + 2md\ddot{\phi}_2 + 2md(d_1 - 0.5d_2)\ddot{\phi}_2^2}{4} + \frac{mg\sin(\phi_1 + \phi_2)}{2},$$

(13)

$$\tau_{\phi_2} = \frac{[md_1^2 + M d_3^2 + 4(M d_2^2 + md^2 + (d_1 - 0.5d_2)^2)]\ddot{\phi}_2}{4} - \frac{md_2}{2}d_2 - \frac{m(2d_2 - d_1)}{2}d_2\dot{\phi}_2 - \frac{[(3M + 2M)d_1 + 2M d_2]}{2}g\cos(\phi_1 + \phi_2) - \frac{(M + 2m)}{2}g\sin(\phi_1 + \phi_2).$$

(14)

Assumption $M = 31kg$, $m = 4.5kg$, $d = 0.24m$, $d_1 = 0.7m$. According to the parameters above, the system simulation results show in Fig.7 and Fig.8.

We may find out from the Fig.7 that the length $d_2$ of the rear arm shortens to ensure the horizontal pose of the body of inspection robot during the down-slope and the upslope path. The adjustment mechanism comes from Eq.1.

Fig.8 shows the angle of inclination of the body. From the fig.8, we may observe that the angle inclination of the body is approximate zero by adjusting the length of rear arm. It is that the body of inspection robot is horizontal state, which ensures that the transmission lines can be observed vertically by the camera.
Fig. 7. Displacement curve of the rear arm

Fig. 8. Curve of angle inclination of the body

Fig. 9. Running with dual arms during up slope state

Fig. 10. Running with dual arms during down slope state

Fig. 11. Inspection robot is hung on the OGWs

Fig. 9 and Fig. 10 illuminate that inspection robot is running on OGWs with dual arms during up/down slope in the laboratory. From the Fig. 9 and Fig. 10, we can see the body of inspection robot is in horizontal pose. This is because the obliquitous sensor exerts its function. When the output of the obliquitous sensor is not zero, that reflects the body is tilt, and the length of arms is adjusted by the corresponding servo motor.

The experiment is carried through in 500KV power transmission lines in Jinzhou, China on April 10, 2006. Fig. 11 represents that inspection robot is hung on the OGWs in real environment by worker. During experiment of initial phase, the pose of body is adjusted to horizontal state by dual arms.
Inspection robot is running on the OGWs with dual wheels, as shown in Fig.12. In the running process, the camera can vertically observe the power transmission lines by continuous adjustment the length of dual arms.

![Fig.12. inspection robot is running with dual wheels](image)

V. CONCLUSION

Pose adjustment control method, which length of dual arms is changed, is presented in this paper. The method enables to keep horizontal pose of the body of inspection by adjusting the length of dual arms of inspection robot. It is that the body of inspection robot is horizontal pose, which ensures that the transmission lines can be observed vertically by the camera. The dynamic model of the pose adjustment mechanism is established when inspection robot is running with dual wheels during down-slope and upslope path. Eventually, the simulation and experiment results test that method proposed is feasible. It is to provide theoretical basis for ultra voltage transmission lines inspection robot design. In the future research, we will consider that the influence of shake of the power transmission lines by wind in real environment.

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