An Autonomous Obstacles Negotiating Inspection Robot for Extra-High Voltage Power Transmission Lines

Xinglong Zhu  Jiping Zhou
Mechanical Engineering College
Yangzhou University
Yangzhou, China
xinglongzhu@263.net

Hongguang Wang  Lijin Fang  Mingyang Zhao
Shenyang Institute of Automation
Chinese Academy of Sciences
Shenyang, China

Abstract—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. 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. After inspection robot configuration is described, the centroid adjustment principle of inspection robot is introduced. Then the control strategy of inspection robot is investigated. From the experiments, we find that the centroid adjustment method proposed and the control strategy presented is feasible.

Keywords—mechamism design, control strategy, inspection of power transmission lines, mobile robot

I. INTRODUCTION

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 negotiate 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 negotiate the metallic tower obstacles. A robot consisting of multi-unit modules is reported in [3]. It can run and negotiate 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 had been investigated for EHV in [7-11]. In recent years, key technology on inspection robot for EHV had been researched in [12-13]. However, because there are so many problems on obstacle-navigation that all the above robots haven’t been applied for real power transmission lines until the present. The research work for the type of robot is still on the way.

This paper describes an autonomous obstacle negotiating inspection robot for EHV power transmission lines. When inspection robot autonomously negotiates obstacles on OGWs, the centre of mass is adjusted to the arm which is hung on OGWs so that the body of inspection robot can keep in horizontal state. At the same time, the method can ensure that inspection robot autonomously negotiates obstacles.

This paper is organized into six sections. The following section, section 2, introduces the obstacles on OGWs, inspection robot configuration, inspection robot prototype and its function. Section 3, introduces the centroid adjustment principle of inspection robot. Section 4, introduces the control strategy of inspection robot. Section 5, brings forth the process of obstacles negotiating by the experiments. The last section of this paper will state the conclusion developed from the experiments.

II. CONFIGURATION OF INSPECTION ROBOT

The main obstacles on the OGWs are counterweights, crimp connection pipes, single overhang anchor clamps and dual overhang anchor clamps, see Fig. 1.
style on a power transmission line. Power department can provide the structure data information of obstacles. Inspection robot can run and negotiate 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.

Inspection robot configuration sees Fig.2. $\theta_1$ 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 $\theta_5$ 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 $O_1fO_1$ 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 $\theta_4$.Fig.3 is the prototype of inspection robot.

III. CENTROID ADJUSTMENT PRINCIPLE

Fig.4 illuminates that inspection robot is hung on OGWs with single arm. Point $a_1$ is the contacting point between the running wheel and OGWs. On the assumption that $r_c$, $r_w$ and $d$ are radius of the round clamping jaw, radius of the running wheel, and diameter of OGWs, respectively. Obviously, $Oc_1 = r_c$, $Oa_1 = r_w$, $a_1a_2 = 0.5d$. $c_1d_1$ is length of clamping line that is between the round clamping jaw and OGWs. It equals as follows,

$$c_1d_1 = 2a_2c_1 = 2r_c \sin \gamma. \quad (1)$$

In (1), the angle $\gamma$ is included angle of straight line $Oa_1$ and $Oc_1$, and its expression is following,

$$\gamma = \cos^{-1}\left(\frac{r_w + d/2}{r_c}\right). \quad (2)$$

According to geometrical relation in Fig.4, we may obtain $a_1c_1 = a_1d_1$ and $a_1c_1$ is as follows,

$$a_1c_1 = \sqrt{a_1a_2^2 + a_2c_1^2} = \sqrt{d^2/4 + r_c^2 \sin^2 \gamma}. \quad (3)$$

In right triangle $\Delta Oa_1b_1$, let $L = a_1b_1$, then

$$L = a_1b_1 = r_w \sin \alpha. \quad (4)$$

In (4), the angle $\alpha$ is include angle between OGWs and horizontal plane.
If the body is kept in horizontal pose, clamping force must be applied on OGWs by left and right clamping jaws. Due the application force causes the friction force $F_f$, the friction torque will balance the gravity torque, and enables the body in horizontal state. If average friction force is $F_f$, then obtains torque equation with respect to $a_1$ point as follows,

$$2F_f a_1 c_1 + m_t g L - (m + M) g (l - L) - m_r g (2l - L) = 0. \tag{5}$$

According to the above equation, the expression of the friction force is as follows,

$$F_f = \frac{(m + M + 2m_t) l - (M + m + m_r + m_t) L}{2 a_1 c_1} g. \tag{6}$$

In (6), $M, m, m_t, m_r$ are mass of the electric appliance box, the body of inspection robot, front arm and rear arm, respectively. $l$ is distance form the body centroid to the arm hung on OGWs. $g$ is gravity acceleration.

Let $M = 20\text{kg}$, $m = 10\text{kg}$, $m_t = m_r = 5\text{kg}$, $l = 0.12\text{m}$, $r_w = 25\text{mm}$, $r_c = 50\text{mm}$, $d = 16\text{mm}$, $\alpha = 15^\circ$, substitution into (1)-(6), and then the friction force is gotten as follows, $F_f = 579.4\text{N}$.

From the above discussion, it is impossible to obtain so bigger friction force. Bigger friction force not only causes damage on OGWs, but also consumes energy resources, and increase weight of inspection robot. In order to solve this problem, the centroid adjustment method is proposed in this paper. The balancing weight adopts the removable electric appliance box which can be moved along the orbits by the servo motor. When the output of the obliquitous sensor is zero, the body will keep in horizontal pose, sees Fig.5.

Assuming the distance of electric box with respect to the front arm is $x$, then obtains torque equation with respect to $a_1$ point as follows,

$$(2F_f a_1 c_1 + m_t g L + Mg (x + L) - mg (l - L) - m_r g (2l - L) = 0).$$

According to the above equation, the expression of the friction force is as follows,

$$F_f = \frac{(m + 2m_t) l - Mx - (M + m + m_r + m_t) L}{2a_1 c_1} g. \tag{7}$$

According to (7), let $F_f = 0$, then the expression of $x$ electric box position is as follows,

$$x = \frac{(m + 2m_t) l - (M + m + m_r + m_t) L}{M}. \tag{8}$$

Substitution the same parameters into (8), $x = 0.10706\text{mm}$. If the error of the control system is $\pm 2$ percent, $\Delta x = \pm 0.02 \times 0.107 = \pm 0.00214\text{mm}$, then the friction force required is following, which will keep horizontal pose of the body,

$$F_f = \frac{M \Delta x}{2a_1 c_1} g = 5.46\text{N}. \tag{9}$$

IV. CONTROL SYSTEM

A. Consist of Control System

The control system of inspection system is composed two parts: they are the body part and the ground monitoring part. The body part consists of PC104 computer embeded, wireless digital transmission transmitter-receiver, servo motors, servo motor drivers, multi-functions card, transducer information acquisition system, power source management system and wireless image transmission system.

The ground monitoring part consists of industrial computer, PCI image acquisition card, wireless digital transmission transmitter-receiver and satellite receiver. The running state of inspection robot is supervised by wireless communication mode in the ground monitoring part. The ground monitoring part can implement telecontrol for inspection robot.

With the exception of the wireless supervision system, there is an autocephaly set of wireless image transmission system. It can check and save images that extra-high voltage transmission lines are taken by cameras. Transducer information acquisition system includes motors limit switches, position switches, coded
disc information, rotary potentiometers, displacement potentiometers, fiber optic sensors and obliquitous sensor.

The on-line acknowledgement sensor which is the fiber optic sensors can inform the control system whether the running wheel had been off-lines is on-lines now. Until acknowledgement, the control system starts new operation.

After the encountering obstacles sensor which is the position switches encounters obstacles, the running motor will stop.

The limit switches control the limit position, the coded disc control the speed of the servo motors, the rotary potentiometers control the absolute rotary angles which the front/rear arms rotate clockwise/anticlockwise direction, the displacement potentiometers control absolute position which the front/rear arms is up/down, and the obliquitous sensor control whether the body of inspection robot is in horizontal state.

The power source management system supervises the state of power source and prevents the under-voltage of power source. Inspection robot has nine servo motors (nine degree of freedom), and distributes in the dual arms and the body. Each arm has four degree of freedom, they are running, fasten/unfasten, rotary and up/down. The centroid adjustment mechanism is drove by the movement motor.

### B. Control Method

After analyzing the working process of inspection robot, the control method is divided into a few stage, they are running control stage and obstacles navigation control stage. The autonomous obstacles navigation mode and manual obstacle navigation mode are adopted in the obstacles control stage. Inspection robot is controlled to negotiate obstacles by the operator with the wireless transmission system in the manual mode. The autonomous obstacles negotiating motion can be obtained by the sensors information, the constrained information of inspection robot and the feedback information in the autonomous obstacles navigation mode. Adopting the stage control can reduce the software complexity, and be propitious to implement the software modularization.

The running motor adopts speed control mode. It is a single input and single output system. The running speed can implement continuous control by PID mode.

The main obstacles on the OGWs are counterweights, crimp connection pipes, single overhang anchor clamps and dual overhang anchor clamps. If inspection robot can autonomous negotiate these obstacles, it should apperceive these obstacles, then select proper motion or motion groups according to the apperceive information. Usually, the process from known information to calculating motion is divided into two phases: apperceive dispose and motion calculation. An eigenvector is produced in the apperceive phase, the autonomous obstacles negotiating motion is obtained by the eigenvector.

In apperceive dispose, the inputs have the constrained formation, sensors information and feedback information, sees Fig.6. A few problems should be taken into account as follows in the apperceive dispose process according to the working task of inspection robot.

![Figure 6. Control principle](image)

1) The dual arms of inspection robot do not allow off the overhead ground lines at the same time.

2) Inspection robot should autonomous negotiate obstacle in precedence order.

3) Inspection robot can recovery the initial state after it completes the autonomous obstacles negotiating.

4) The autonomous running obstacles negotiating is superior to the autonomous rotary obstacles negotiating.

The expression and action of the motion functions have many researches, i.e. the network mode and the generated mode. We select the generated mode to express the motion functions in this paper. A generated system includes a rules set. Each rule can express “c→a”, c is the condition term, a is the action term.

In order to realize the autonomous obstacles negotiating, the process of obstacles negotiating is divided into many actions which are mutual independence. These actions are divided into four groups, ten actions in all.

The first group: front and rear arm are on/off the overhead ground wires.

The second group: front or rear arm, and front and rear simultaneous, is running on the overhead ground wires.

The third group: inspection robot rotates by front or rear arm.

The forth group: inspection robot adjusts its mass centre.

### C. Auxiliary Control

Reliability and security are very important for a control system which applies in practical engineering. Abnormal dispose capability can ensure whether the control system is reliable and secure in operation or not. Some special faults are encountered in practical operation, i.e. the devices faults, sensors faults and so on. Auxiliary control system takes into account the four problems as follows.

1) Communication breakaway between the body part and the ground monitoring part. When communication happens breakaway, inspection robot should stop running, and avoid
abnormality. If the body part and the ground monitoring part can not establish handshake signal, inspection robot will autonomous return to initial point according to the recorded distance.

2) Under-voltage of power source. The alarm system of under-voltage of power source is equipped so that inspection robot can return proximate safety zone.

3) Collision avoidance. The position switches are equipped in the running and gripping mechanism. When inspection robot approaches the obstacles, the sensors sent out the signal. When the control system receives the signal, the running motor will stop, and therefore inspection robot avoids collision.

4) Validity confirmation of transmission data. In electromagnetic disturbance, single data may be occurred errors during transmission process. In order to prevent these mistakes, the confirmation mode adopts the average of which all transmission data is.

V. EXPERIMENTS

In order to prove the correctness of the method proposed, we simulate the environment of the ultra high voltage power transmission lines in the lab. There are two counterweights, single overhang anchor clamps in the environment, sees Fig.7.

![Figure 7. The environment of the EHV power transmission lines](image)

Fig.8a denotes that inspection robot encounters the obstacle—the counterweight and stops on OGWs. The electrical box is moved over the rear arm. The front arm is up and off OGWs, inspection robot is running with rear wheel until it encounters the counterweight and stops, sees Fig.8b. The front arm is down and on OGWs, sees Fig.8c. Then the electrical box is moved over the front arm, the rear arm is up and off OGWs, inspection robot is running with the front wheel, sees Fig.8d. Next step, inspection robot encounters the obstacle—single overhang anchor clamp and stops on OGWs, sees Fig.8e. Fig.8f denotes that inspection robot is rotating by the front arm, and Fig.8g denotes that process of the rear arm is down and on OGWs. Fig.8h denotes that inspection robot is rotating by the rear arm. After two continuous rotary, inspection robot negotiates the single overhang anchor clamp. The current state is that the rear arm is on OGWs, the front arm is off OGWs. Inspection robot is running with rear wheel, sees Fig.8i. When real wheel encounters the counterweight again, inspection robot will stop, sees Fig.8j. Then the front arm is down and on OGWs. At the same time, the electrical box is moved to the front arm, sees Fig.8k. The last step, sees Fig.8l, the electrical box is moved over the front arm, the rear arm is up and off OGWs again, and inspection robot is running with the front arm until it negotiates the counterweight and stops. Eventually, inspection robot resumes dual arms running mode after if has been negotiated these obstacles.
In this paper, an autonomous obstacles negotiating inspection robot for EHV power transmission lines is introduced. It can find damages of extra-high voltage power transmission lines equipment. After inspection robot configuration and its function are described, the centroid adjustment principle of inspection robot is introduced. Then the control strategy of inspection robot is investigated. Eventually, the process of obstacles negotiating is brought forth through the experiments. From the experiments, we find that the centroid adjustment method proposed and the control strategy presented is feasible. Inspection robot can implement autonomous obstacles negotiating.

**VI. CONCLUSION**

Figure 8. The process of obstacles negotiating

In this paper, an autonomous obstacles negotiating inspection robot for EHV power transmission lines is introduced. It can find damages of extra-high voltage power transmission lines equipment. After inspection robot configuration and its function are described, the centroid adjustment principle of inspection robot is introduced. Then the control strategy of inspection robot is investigated. Eventually, the process of obstacles negotiating is brought forth through the experiments. From the experiments, we find that the centroid adjustment method proposed and the control strategy presented is feasible. Inspection robot can implement autonomous obstacles negotiating.

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