The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Development of an Inspection Robot for 500 kV EHV Power Transmission Lines

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Abstract — **The developments in mobile robotics have increasingly played an important role in the inspection and maintenance work of Power Transmission Lines (PTLs). This paper presents the research and development of the inspection robots for 500kV PTLs in Shenyang Institute of Automation, Chinese Academy of Sciences (SIACAS). An overview of the research work and the development of an inspection robot AApe-B, are introduced, respectively. The AApe-B can run on the Overhead Ground Wires (OGWs) and navigate different types of obstacles in remote and locally autonomous control mode. A novel dual-wheel-arm hybrid mechanism with the excellent locomotion and obstacle-navigation performance is designed, and obstacle navigation process is analyzed. An embedded control system which can withstand the strong electromagnetic interference has been developed. A lot of field experiments have been carried out, and the experimental results have shown that the inspection robot can reliably work during the 500kV Extra High Voltage (EHV) electromagnetic environment and possess the primary ability to implement the inspection task of the 500kV PTLs.**

I. Introduction

The purpose of inspecting Power Transmission Lines (PTLs) is to obtain running conditions and find damage of the transmission lines. Presently, this inspection task has been carried out manually by a worker with a telescope on the ground [1]. To improve inspection quality, the worker sometimes has to climb up the towers and ride in a gondola suspended on the Overhead Ground Wires (OGWs). The manual inspection method has many disadvantages, such as long inspection cycle, high working intensity and risk [2]. A helicopter with a video camera is also used to inspect PTLs. However, this method is very expensive and easily influenced by the climatic and geographical condition.

The development of mobile robots provides an alternative means for inspecting PTLs. Using a mobile robot to inspect the PTLs, the disadvantages of the two methods mentioned above can be effectively avoided. The method has higher inspection precision than the manual inspection, lower cost than the helicopter inspection, and so on [1]. Hence, the research of the mobile robot for inspecting PTLs has become a hot topic, and some robot prototypes have been developed [2].

A robot prototype for inspection of the 66kV fiber optic overhead ground wires is described in [1], which can run on the OGWs and navigate such obstacles as counterweights and clamps. The inspection robot consisting of dual arms, 4 sets of actuators and crawlers has been developed to run on the OGWs and navigate tower obstacles in [2]. The inspection robot consisting of multi-unit modules has been developed to run and navigate obstacles on telephone wires and PTLs in [3]. Since the developed robot prototype has 18 degrees of freedom, the battery with large capacity is required to power the inspection robot. The mobile mechanism with biped configuration is proposed for inspecting PTLs in [4]. For preventive maintenance of high voltage PTLs, the remotely operated inspection robot with mobility has been developed to navigate cable spacers, suspension clamps and other obstacles in [5]. In [6], the mobile robot for inspecting 220kV double circuit transmission lines has been developed, which has 7 degrees of freedom, double anti-symmetrical retractable arms, interactive sliding and suspending structure. The inspection robot prototypes for 500kV Extra High Voltage Power Transmission Tines (EHVPTLs) has been developed in [7]. After the inspection robot named LineROVer was developed for 315kV PTLs de-icing, visual and infrared inspection, etc in a span [8], the team at Hydro-Quebec research institute (IREQ) develops another inspection robot named LineScout, which can not only run on 735kV EHVPTLs and navigate most obstacles on the line, but also can be equipped with a variety of tools for maintenance tasks, such as repairing broken conductor strands [9]. Many other types of inspection robot prototypes can be found in [10-12]. Although many great improvements have been achieved in the research works above, there are still lots of key techniques which need to be settled for the practical application, such as the mechanism optimal design, the control reliability, and the power acquiring from live lines.

Supported by the National High Technology Research and Development Plan (863 Plan) of China, the State Key Laboratory of Robotics, Shenyang Institute of Automation,

Manuscript received March 12, 2010. This work was supported in part by the National High Technology Research and Development Program of China under Grants 2002AA420110-1 and 2006AA04Z203, and the State Grid Corporation of China Science and Technology Project under Grant (2006) 18.

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Chinese academy of sciences (SIACAS), has been engaged in the development of mobile robots for the 500kV EHVPTLs since 2002. The research group has solved many technical problems of the robot used under the 500kV extra high voltage environment innovatively, such as robot mechanism, control, electromagnetic compatibility, insulation, long-distance communication and other key technologies, developed a series of the novel EHVPTLs inspection robots with the completely proprietary intellectual property rights, and implemented a lot of inspection tests on the live wires with 500kV. In this paper, an overview of the research work and the recent development of an inspection robot, AApe-B, are introduced respectively. With a centroid adjustment mechanism and a dual-wheel-arm hybrid mechanism, the AApe-B can run on the OGWs, and navigate different types of obstacles in autonomy and remote control mode. An embedded control system which can withstand the strong electromagnetic interference has been developed. Field experimental results have shown that the inspection robot can reliably implement the inspection task of the 500kV EHVPTLs.

The remaining of this paper is organized as follows: The overview of the completed research work and the recent development of an inspection robot are presented in Section II and III, respectively. In Section IV, the results of field experiments and tests are discussed. Finally, some conclusions and future works are given in Section V.

II. Overview of the Research Work

A. Background

The EHVPTLs are the main network of electric power in China, so the security and reliability of the power grid are quite important. So far, the EHVPTLs are still inspected manually by a worker with a telescope on the ground. This working mode has many disadvantages, such as a long inspection cycle, high working intensity, huge expense and high danger. The equipments which can inspect the power lines autonomously are eagerly expected to replace human from the inspection work completely or partly.

Since 2002, supported by the National High Technology Research and Development Plan (863 Plan) and the Science and Technology Project of the State Grid Corporation of China, SIACAS, cooperated with the Northeast China Grid Company Limited, has been engaged in the development of mobile robots for inspecting the 500kV EHVPTLs. The ultimate goal of the research is to solve the key techniques, develop the EHVPTLs inspection robot system with the completely proprietary intellectual property rights, carry out the laboratory and field tests, and lay the foundation for the field application of the inspection robot in the 500kV PTLs.

B. Research Course

Up to now, two series of prototypes (named AApe-A and AApe-B, respectively) have been developed, and many great achievements have been made. The course and achievements of these research works are as follows:

--From 2002 to 2006, the key techniques including the mobile mechanisms for one span and for large inclination angle lines, the control system in the strong electromagnetic environment, and the long-distance data/image transmission, were implemented. In this stage, a series of prototypes AApe-A were developed, as shown in Fig. 1. The AApe-A1 is the inspection robot for one span, and the AApe-A2 is the inspection robot for large inclination angle lines.

--From 2007 to present, the solved key techniques includes locomotion and obstacle-navigation mechanism, state monitoring system, remote and locally autonomous control method, fault identification and safety protection etc. In this stage, the prototype AApe-B was developed, which has been tested on the 500kV live lines, and passed the field performance tests in the Northeastern Electrical Equipment Quality Test Station, as shown in Fig. 2.

AApe-A1 AApe-A2

Fig. 1 AApe-A series inspection robots.

Fig. 2 AApe-B inspection robot and field performance tests.

The innovation of the above works lies in developing the 500kV EHVPTLs inspection robot with the completely proprietary intellectual property rights, designing a new type of dual-wheel-arm hybrid mechanism with the excellent locomotion and obstacle-navigation performance, and establishing a control mode which combines remote control with locally autonomous control under strong electromagnetic environment. Four patents for invention and seven patents for utility model have been granted during the process of completing the projects.

In this paper, taking the prototype AApe-B for instance, the research and development of an inspection robot for the 500kV EHVPTLs are introduced.

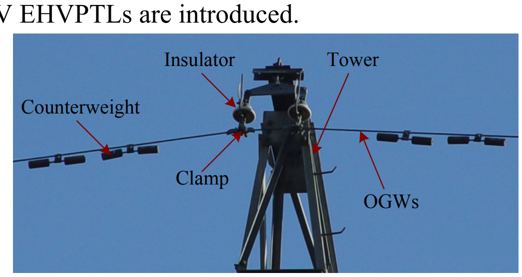


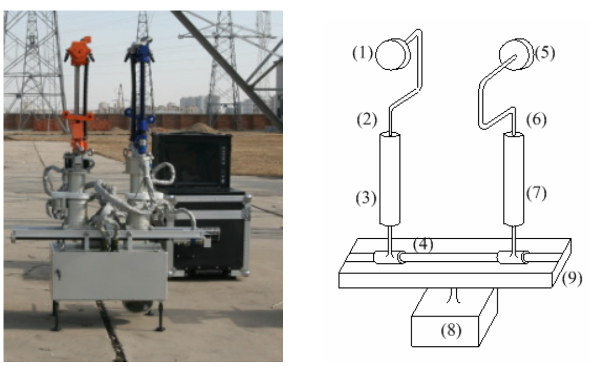
Fig. 3. Obstacle configurations on OGWs for 500kV EHVPTLs

III. Development of an inspection robot AApe-B

A. *Inspection Task and Environment*

The EHVPTLs need to be inspected periodically. The inspection purpose is to know the running conditions and the environment along them, detect the equipment fault in time, and provide the information for maintenance. According to the requirements of "overhead transmission lines operating regulation", the main contents of the EHVPTLs inspection include: 1) the strand breakage of the transmission lines; 2) the power grid crossings (trees, quarries, buildings etc.); 3) the steel towers, the pole braces and the foundations; 4) the fittings and the insulators.

The environment of the 500kV EHVPTLs is quite complicated, consisting of passage way, PTLs, OGWs, straight line towers, strain towers and other electric power equipments. The typical obstacle configurations on the OGWs for the 500kV EHVPTLs are shown in Fig. 3. The counterweight is used to decrease the influence of the wind vibration and protect the fittings. The suspension clamp is used to root the ground wire to the tower. Obviously, a mechanism with the excellent locomotion and obstacle-navigation performance is necessary so that the inspection robot can run on the OGWs and navigate different types of obstacles.



(a) Real photo (b) Kinematic sketch of mechanism

Fig. 4. Inspection robot AApe-B.

B. *Composition and Function of the Inspection Robot AApe-B*

The inspection robot AApe-B is composed of a mobile robot and a ground base station, as shown in Fig. 4. The mobile robot consists of a power, a robot body, a controller, an on-board wireless data and image transmission system and a video camera. The ground base station includes a generator, a monitoring system, a ground wireless data and image transmission system and a monitor. The inspection robot AApe-B can run on the OGWs and navigate many types of obstacles in remote and locally autonomous control mode. The PTLs damage condition can be detected by an on-board video camera and the image can be transmitted to the ground base station to store and process. The mobile robot can be remotely controlled and monitored by the ground base station.

Two separate transmission system is adopted so as to ensure the reliability of data and image transmission. The robot AApe-B possesses the primary ability to implement the inspection task of the PTLs.

C. *Description of the Mechanism System*

The configuration of the developed inspection robot is shown in Fig. 4 (b). The inspection robot consists of fore/rear grippers (1) and (5), fore/rear revolute joints (2) and (6), fore/rear prismatic joints (3) and (7), prismatic joint (4), body (8) and centroid adjustment mechanism (9). The fore/rear grippers (1) and (5) are coupled with fore/rear wheels, respectively, for carrying out the movement of the inspection robot on the OGWs with the large inclination angle up to 30 degree. With the fore/rear revolute joints (2) and (6), the revolute movements of the grippers (1) and (5) can be completed. With the revolute joints (2) and (6) and the prismatic joints (3) and (7), the inspection robot can navigate obstacles such as counterweights and clamps. With the help of the subsidiary rail and the prismatic joint (4), the distance between the rear and fore arms can be adjusted for the inspection robot to navigate different types of obstacles. At the bottom of the body (8), a camera is installed for monitoring the conditions of the inspected PTLs. For short, the combination joints (1)-(3) are called the fore arm, while the combination joints (5)-(7) are called the rear one.

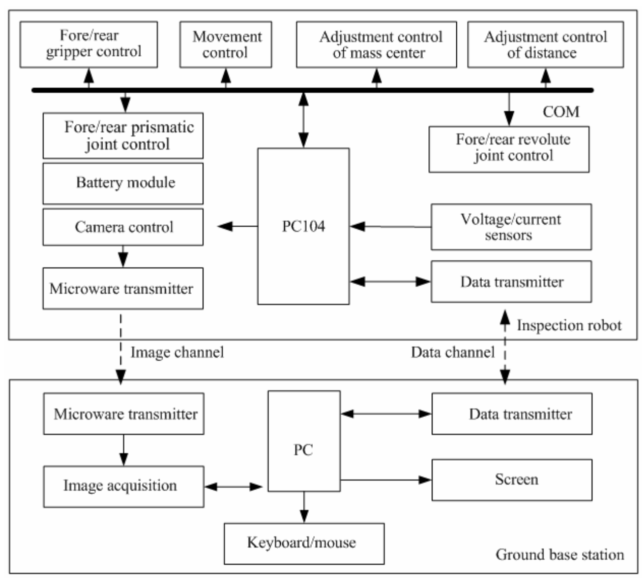


Fig. 5. Control system of the developed inspection robot.

D. *Control System Design*

Control system structure

The whole control system consists of the ground base station and the robot control system, as shown in Fig. 5, respectively. The control system of the inspection robot can realize motion control, obstacle navigation control, camera control, wireless data and image transmission, state estimation of the battery onboard. Considering the requirement of size, weight, reliability and processing capability, an embedded computer PC104 is chosen as the core of the control system. The camera control can complete the image acquisition of the inspection PTLs. The control commands and the state data are transmitted between the robot and the ground base station by a couple of wireless data modems, and the images are transmitted from the robot to the ground base station by a set of wireless image transmission device. The battery module is used to monitor the state of battery onboard, such as the charge and the health, and provide the estimation of the remaining time. The data transmission channel and the image transmission channel are separated each other.

The ground base control system consists of an industrial computer, an image acquisition, a microwave receiver, a data modem and a monitor. The main task of ground base control system is the remote control for the inspection robot. It can make the robot forward, stop, and back, and control the robot to navigate obstacles. The ground operators can control the inspection robot via the human-computer interface.

Electromagnetic Shielding

Because of a high Electromagnetic Field (EMF) around the running 500kV EHVPTLs, there is an induced current or an induced voltage on the OGWs and the inspection robot. In order to reduce the EMF effect on the performance of the inspection robot, the robot must work on the grounding mode of the OGWs [10].

The EMF can affect the robot controller and make the robot work abnormally, and even destroy the robot circuits directly. The electromagnetic shielding for the robot includes static electric field shielding and EMF shielding. The static electric field shielding is based on Farady cage theory [10]. The copper paper can be used as the electric field shielding material. However, the cooper paper is too flexible to brace the robot shell, so the dual-layer structure of cooper and aluminum is used in the developed inspection robot. Besides, the shell of the inspection robot is also required to form a good electric and magnetic conductor based on electromagnetic shielding, so it is necessary to reduce the number and size of holes and gaps.

State Monitoring

The states of the inspection robot need to be monitored in real-time for autonomous obstacle navigation and healthy state management. During the running process of the inspection robot, the position and orientation, battery and ambient environment, need to be monitored in real-time. The monitored position and pose are used for assuring the robot stability, reliability, and inspection quality; the monitored battery states include voltage, current, state of charge, state of health, and so on; the ambient environment is monitored for avoiding and navigating obstacles such as clamp, counterweight and tower. Besides, during the process of the locally autonomous obstacle navigation, the part of the states of the inspection robot is monitored by an operator through a human-computer interface on the ground base station.

E. Obstacle Navigation Analysis

According to the configuration of the developed inspection robot, the process of obstacle navigation can be realized by two modes, namely rotate mode and cankerworm mode. For the obstacles such as counterweight, the inspection robot can navigate the obstacles by lifting the fore/rear arms in turn in the cankerworm mode. For the obstacles like clamps, since the fore/rear grippers can not pass over the obstacles even though the fore/rear arms had been lifted to the maximal range, the obstacle navigation is carried out in the rotate mode. Taking a counterweight obstacle as an example, the detailed descriptions of the two obstacle navigation modes are as follows.

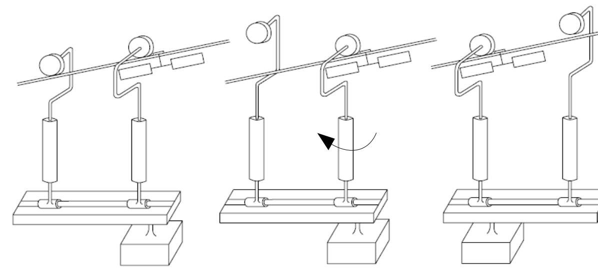


Fig. 6. Obstacle navigation in the rotate mode.

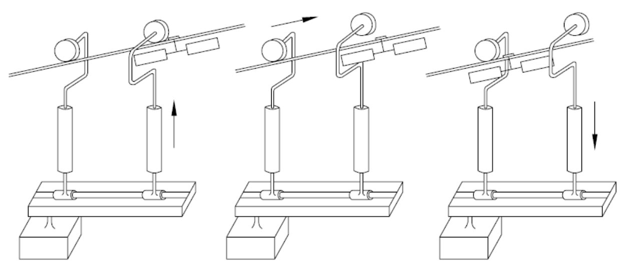


Fig. 7. Obstacle navigation in the cankerworm mode.

Obstacle Navigation in the Rotate Mode

As shown in Fig. 6, when the inspection robot encounters a counterweight obstacle, the process of obstacle navigation in the rotate mode is given as follows: Step 1: the rear arm extents until it is higher than the counterweight obstacle; Step 2: by rotating the fore arm, the rear one will cross over the obstacle; Step 3: with the camera mounted on the rear gripper, the OGWs is located, and the rear arm is controlled to grasp the ground wire behind the navigated obstacle. Hence, the inspection robot can navigate obstacles by rotating the two arms and repeating above steps.

Obstacle Navigation in the Cankerworm Mode

As shown in Fig. 7, when the inspection robot encounters a counterweight obstacle, the process of obstacle navigation in cankerworm mode is described as follows: Step 1: the fore arm extents until it is higher than the counterweight obstacle; Step 2: the rear arm drives the robot moving forward until the rear one encounters the counterweight obstacle. Hence, the fore arm is behind the obstacle; Step 3: with the camera mounted on the fore arm, the OGWs is located, and the fore arm is controlled to grasp the ground wire behind the navigated obstacle. The inspection robot can navigate obstacles by lifting the two arms and repeating above steps.

Both of the two modes have their advantages and disadvantages. Obstacle navigation in the cankerworm mode is time saving but it is easy to be interfered by the ambient environment like the wind or vibration of the OGWs, since it have to drive the robot moving forward with only one arm on line. On the contrary, the obstacle navigation in the rotate mode is stable but it spends more time in navigating obstacles than that in the cankerworm mode. This is because both of the two arms should be rotated alternatively.

Counterweights and suspension clamps are the common obstacles near the straight line tower. The robot AApe-B can navigate these obstacles by a combination of the two different navigation modes mentioned above. When the robot gets close to the counterweight, as shown in Fig. 8 (a), it can navigate the obstacle in the cankerworm mode. In order to save time, the fore arm keeps stretching out so that the robot can directly get into the rotate mode to navigate the clamps, as shown in Fig. 8 (b). During the clamp navigation, there is a sufficient gap for the rear wheel between the clamps, as shown in Fig. 8 (c). Hence, the repeat performance of the rotate mode makes the robot navigate the clamps, as shown in Fig. 8 (d).

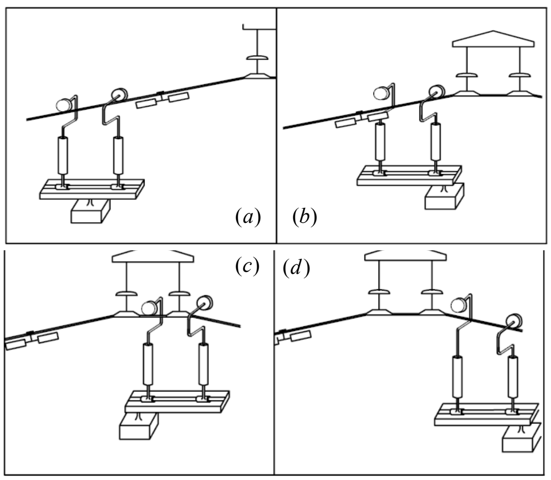


Fig. 8. Process of navigating obstacles near a straight line tower.

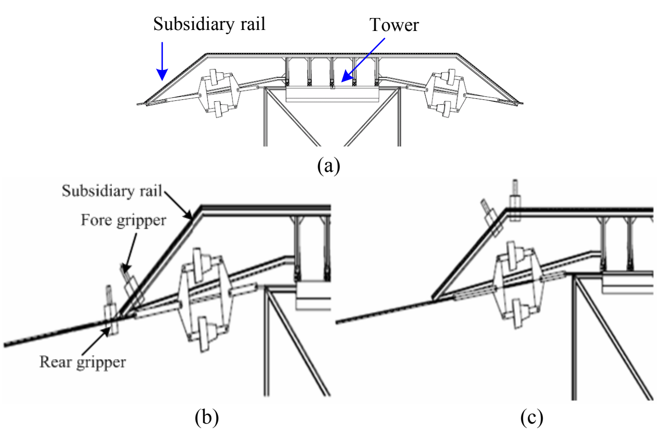


Fig. 9. Process of navigating a strain tower. (Vertical view)

As the environment near the strain tower is more complex than the straight line tower, the robot AApe-B navigates the strain tower in a combination mode of the cankerworm mode and the rotate mode with the subsidiary rail, as shown in Fig. 9 (a). Before the robot reaches the subsidiary rail, the arms are regulated to the same side far away from the tower. Hence, the fore arm of the robot expands in the cankerworm mode, and the rear one drives the robot moving forward for a distance, until the fore arm is above the rail. By the revolution of the arms, the fore wheel can be located on the rail, as shown in Fig. 9 (b). With the same process, the rear wheel can be also located on the rail, so that the robot gets on the rail. The robot can get across the two corners on the rail, as shown in Fig. 9 (c), and get off the rail and with the same method to navigate the strain tower.

IV. Field Experiments

In order to verify if the prototype AApe-B can work properly in the 500kV EHV environment, field tests have been carried out by the Northeastern Electrical Equipment Quality Inspection Station of China.

The test Results indicate that:

--The AApe-B is able to work properly on the 500kV EHV power transmission lines;

--The measures of electromagnetic shielding are reasonable, and the robot has a strong ability of anti-electromagnetic interference;

--The movement velocity and the obstacle navigation meet the practical requirements of the live line inspection;

--The transmitted data and images are clear.

For testing the practical functions of the prototype AApe-B, the comprehensive field experiments have been carried out on the 500kV EHVPTLs in the northeast area of China.

The experimental purpose is to test the reliability of the communication system, the anti-electromagnetic interference ability of the control and video systems, the ability to run along the OGWs, the ability to navigate the obstacles during crossing the straight line and strain towers, the functions of remote control and monitor between the ground base station and the robot, and the operating performance of the live line inspection. Field experimental results and inspection images are shown in Figs. 10 and 11, respectively.


(a) navigating a straight line tower (b) navigating a strain tower
Fig. 10. Field experiments.

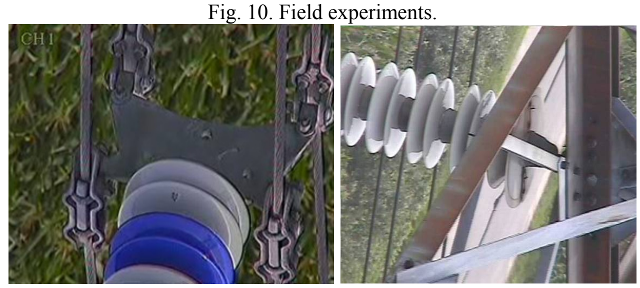


Fig. 11. Inspection images.

The results of the field comprehensive experiments show that:

--The robot prototype AApe-B works fluently in the field 500kV EHV electromagnetic environment.

--The dual-wheel-arm hybrid locomotive mechanism can complete the obstacle navigation by the remote and local autonomous control.

--The communication between the ground base station and the robot is reliable.

--The control method of the inspection robot is effective.

--The hardware and software of the inspection robot system are stable and reliable.

The performance indexes of the AApe-B are shown in Table I.

TABLE I
Performance indexes of AApe-B

Voltage of PTLs	500kV
Dimensions	760mm×360mm×1050mm
Weight	42kg
Traveling speed	1. 25km/h
Inclination angle lines	30°
Distance of video wireless transmission	5km

The inspection robot prototype AApe-B possesses the primary ability to replace a worker to implement the inspection of the 500kV EHVPTLs.

V. Conclusion and Future Work

In this paper, the research and development of the inspection robots for 500kV EHVPTLs in SIACAS are presented, which include an overview of the completed work and the latest development AApe-B. The key technologies on the dual-wheel-arm hybrid mechanism with the excellent locomotion and obstacle navigation, the obstacle surmounting process and the embedded control system with the ability of anti-electromagnetic interference, are discussed respectively. The results of the EHV live tests and the field comprehensive experiments indicate that the AApe-B is able to work properly on the 500kV EHVPTLs; the dual-wheel-arm hybrid locomotive mechanism can complete the obstacle navigation by the remote and local autonomous control; the robot has a strong ability of anti-electromagnetic interference; the communication between the ground base station and the robot is reliable. The inspection robot prototype has the primary ability to replace human to implement the inspection of the 500kV EHVPTLs. The future work should mainly be oriented toward the optimum design of the mechanical structure, the reliable obstacle detection and identification, the battery technologies, and the sensor fusion to improve the autonomous level.

Acknowledgment

The authors would like to thank Yifeng Song, Weibin Guo, Libo He and Lie Ling for their contributions to this paper.

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