Development of a Bio-inspired Live-Line Cleaning Robot for Suspension Insulator Strings

Lin Wang¹,², Hong-guang Wang¹, Yi-feng Song¹, Xin-an Pan¹

¹State Key Laboratory of Robotics, Shenyang Institute of Automation, Shenyang 110016, China; ²University of Chinese Academy of Sciences, Beijing 100049, China

Abstract — Exposed porcelain insulator strings need regular cleaning to prevent power failures caused by flashovers from occurring. Live-line cleaning of insulators using robot technology is an alternative and novel approach to removing the contaminants on the surfaces of the insulator. This paper presents a live-line insulator cleaning robot for suspension insulator strings in 500kV power transmission lines. After analyzing the cleaning task, we introduce the mechanical system composed of the inchworm-based locomotion mechanism and the cleaning mechanism. The details of the mechanical design are given. The control system composed of the local controller and the ground control station is implemented. The hardware of control system is based on the Digital Signal Controller and the software is developed based on the Real Time Operating System. The motion planning algorithm for the cleaning task is presented. The motion planning model is established in Matlab and simulation results prove the correctness of the motion planning algorithm. Preliminary experiments are carried out, and the results demonstrate the validity and the feasibility of the robot.

Keywords—insulator cleaning robot; mechanical design; control system design; software design; motion planning algorithm

I. INTRODUCTION

The insulators, which are one of the vital components of power transmission lines, are intended for mechanical fixings and electrical insulation of conductors. Exposed insulators are subject to surface dirt deposits in all operating areas. Dirt on the surfaces has no damaging effect on the normal running of insulators when the surfaces remain dry. However, when the insulators get wet, the pollutant on the surfaces of the high voltage insulators can create a conductive path, resulting in leakage currents and flashovers which may lead to power failures [1]. Insulator cleaning is a practical and commonly used way to remove the contaminants on the insulators. Ceramic and glass insulators can be cleaned in a number of ways such as water washing, hot wiping using a live-line tool and hand wiping [2]. Hand wiping using wet cloth and dry wiping rags is the most commonly used cleaning method in China, as shown in Fig. 1. The method is effective and practical, but it’s very time-consuming, tedious, dangerous and expensive in terms of outage time and cost. Compared to hand wiping and other cleaning methods, cleaning insulators using robots is advantageous in enhancing linemen’s safety, increasing efficiency, reducing costs and providing access to hard-to-reach locations.

A number of research teams have been working on insulator cleaning robots for decades. Early work mainly focused on the functional implementation and mechanical design of robots capable of moving along insulator strings and cleaning insulators. In 1992, Paris [3] introduced an apparatus which can carry out live-line maintenance work such as cleaning insulator strings for suspension insulator chains. The mechanism is mainly consisted of the locomotion mechanism which is comprised of at least one track rotating on two transmission rollers driven by at least one motor, several spraying nozzles and a guide body surrounding the insulator string. In 1993, Hu [4] proposed an automatic washing-brushing robot for 500kV DC insulator chains. Water jetting and rotating brushes are used to clean the surfaces of the insulators. Other researchers [5-8] presented some conceptual designs.

Figure 1. Cleaning insulators by hand wiping.

Among the various researches in this field of robotics, only a few resulted in complete prototypes which can perform cleaning tasks under live-line conditions. Hirose [9] developed an insulator washing robot for substation insulators. The robot is composed of an orbit rail, a cylindrical coordinate type arm and a rotating washing unit. The prototype weights 175kg and it takes 150 minutes to finish cleaning three sets of insulators on the steel tower. Che, Gu and Yang [10-11] presented a hot-line robot intended for sweeping post insulators. The robot cleans the substation insulator using rotating brushes and the moving carrier is a refitted truck. The prototype was developed and the performance test was carried out. Korea Electric Power Research Institute developed an insulator inspection and
cleaning robot for double tension insulator strings in 345kV power transmission lines [12-13]. The insulation resistance is measured to detect faulty insulators and the dry cleaning method with two rotating brushes is used to clean contaminated surfaces of the insulators. The robot can perform inspection and cleaning task autonomously and manually. In 2009, another inspection and cleaning robot for suspension insulator strings is presented [14]. The structure of this robot is very similar to that of the previous robot and the wing connection mechanism is re-designed so that the robot can be applied to suspension insulator chains. Other researchers introduced several robot prototypes [15-19] which are able to move along the insulator strings and perform maintenance tasks such as insulator inspection.

From the literature related to the theme of insulator cleaning robots for power transmission lines, we found few prototypes capable of cleaning insulator under live-line conditions have been developed and they are used in particular situations. Besides, much work should be done to improve the robot's adaptability to the working environment. To the knowledge of the authors, the robot which can perform cleaning task for the double umbrella type porcelain insulator has not been studied. Our research aims at developing a live-line insulator cleaning robot for suspension insulator strings composed of the double umbrella type porcelain suspension insulator in 500kV power transmission lines. The remainder of the paper is organized as follows. Section II analyzes the cleaning task and derives the requirements the robot should meet. In Section III, inspired by the locomotion of the inchworm, taking into account the task environment, we propose the insulator cleaning robot mechanism and give the details of mechanical design. The control system design is presented in Section IV. Moreover, the motion planning algorithm is introduced. Simulation of the motion planning model and preliminary experiments in the laboratory are carried out in Section V. Finally, the conclusions of this study are drawn.

II. TASK ANALYSIS

A. Analysis of Task Environment

In this paper, the double umbrella type porcelain insulator, which is widely used in suspension insulator strings of 500kV power transmission lines, is to be cleaned. Fig. 2 shows working environment of the robot.

![Figure 2. (a) An insulator set for a 500kV line; (b) structure of the insulator; (c) parameters of the porcelain insulator.](image)

The insulator is a semi-structural object with three given parameters, i.e. the shed spacing, the shed diameter and the leakage distance. The shape of the porcelain shed of the insulator is complicated and irregular. Moreover, the shape of a specific type of insulators designed by different manufacturers may differ a lot. Electric field distributes not evenly on the suspension insulator string. For safety reasons, the effective length of the operating rod shouldn’t be less than 4 meters when the linemen performs live-line maintenance task [2]. The working environment of the robot is hazardous. Special attention should be paid to the mechanical structure design and the control system design.

B. Analysis of Cleaning Task

The pollutants in the atmosphere are gradually depositing on the surfaces of the insulators due to the forces acting on the particles of the contaminants. The forces include the wind, the gravity and the electric forces in a non-uniform electric field. Diverse kinds of dust in industrial areas such as steel mills, and other pollutants have components which are highly conductive when moistened. The contaminants on the surface of the insulators are of different types and they may be difficult to remove as they strongly adhere to the insulators.

Hand wiping is widely used to clean the dirty insulator strings. When the conductors of the power transmission lines are de-energized, the linemen start to clean the insulators piece by piece with dry wiping rags and wet cloth from the earthed end of the insulator set to the energized end of the insulator string. They firstly clean the surfaces of the insulators with wet cloth and then wipe them with the dry wiping rags.

C. Development Requirements for Robot System

The insulator cleaning robot performs cleaning task under live-line condition in hard-to-reach locations. The following requirements should be satisfied:

- **Mobility**: The robot should be able to move along the suspension insulator string composed of the double umbrella type suspension insulator without damaging the RTV coatings on the surfaces of insulators.
- **Autonomy**: The robot should be able to perform cleaning task autonomously, and remote control is inevitable as unexpected situations may occur.
- **Electromagnetic Compatibility**: Appropriate and practical electromagnetic compatible techniques should be applied to the robot to ensure the reliable running of the robot under live-line conditions.
- **Adaptability**: The robot should adapt to the variations of dimensions of the insulators as each piece of the insulators may differ slightly.

III. MECHANICAL DESIGN

A. Principles of Inchworm Locomotion

Caterpillars are one of the most successful climbers and can maneuver flexibly in non-structural environment [20]. They are consisted of a head, a thorax with three pairs of
jointed leg with hooks, and an abdomen with five pairs of stumpy prolegs. The caterpillar moves via muscular contractions which proceed from the rear of the animal to its front. There are two locomotion modes of caterpillars and the locomotion principle of the inchworm (Fig. 3) is briefly illustrated in Fig. 4. Two adhesion modules and some revolute joints are used to depict the movement of the inchworm. When the inchworm performs the gait to move, two adhesion modules alternatively adheres the wall while the body contracts or stretches accordingly.

The inchworm is able to cross large obstacles with abrupt changes in curvature as it remains stable without having all legs on the ground. Inspired by this great advantage, this paper proposes the insulator cleaning robot mechanism based on inchworms because the curvature of the insulator changes sharply.

B. Overall Structure
The insulator cleaning robot mainly includes the inchworm-based locomotion mechanism which enables the movement along the suspension insulator string, the cleaning mechanism which accomplishes the cleaning process of contaminated insulators, the frame and other modules such as the control modules and batteries. Fig. 5(a) is the kinematic diagram of the robot mechanism. The 3D model of the insulator cleaning robot is shown in Fig. 5(b).

C. Locomotion Mechanism
The locomotion mechanism is the basis of the robot and provides motion along the suspension insulator set. The locomotion mechanism is consisted of a fixed platform attached to the frame of the robot, a slidable platform capable of moving relatively to the fixed platform along the axis of the insulator chain, and a frame. Each platform is equipped with a grasping mechanism which engages the socket cap of the porcelain insulator.

The grasping mechanism is comprised of a DC servo motor, a worm drive, three spur gears, two arms extending outwardly from the platform, two shafts, two grippers and some springs, as seen in Fig. 6. The grippers of the platform can transit between a closed position where the grippers engage the cap of the insulator with the force big enough to withstand the self-weight of the robot and an open position where there is no interference between the robot and the insulator string when the robot moves.
suspension insulator set and the distance between two platforms are two times the shed spacing of the insulator. When moving downwards, it first opens the grippers of the fixed platform, moves the slidable platform to a position where the distance between two platforms is the shed spacing of the insulator, and then closes the grippers of the fixed platform. Then it opens the gripper of the slidable platform, moves the slidable platform to its initial position, and finally closes the grippers of the slidable platform. The gait is completed and the robot moves down an insulator.

The aforementioned locomotion mechanism engages the cap socket of the insulator, thus the robot would not damage the RTV coatings on the shed of the porcelain insulator. Besides, it can adapt to changes of the shed diameter in a certain range. The robot can also adapt to changes in the distance between two adjacent insulators as the maximum distance between the fixed platform and the slidable platform is larger than two times the shed spacing of the insulator.

D. Cleaning Mechanism

Compared to other cleaning methods, the dry cleaning method is much more practical as the structure of the live-line cleaning robot may be simple and compact. Thus, brushes made of nylon bristles are chosen to remove the pollutants on the surfaces of the insulators. A prismatic joint which enables the cleaning mechanism move along the axis of the insulator chains is necessary because the robot should clean two umbrellas of the insulator. A cleaning platform including the cleaning mechanism and the lifting mechanism is proposed to perform the cleaning process on the two umbrella type porcelain insulator, as shown in Fig. 8.

The cleaning mechanism is consisted of a circular motion guide fixed on the plate of the platform, a slider mounted on a big spur gear, three rotating brushes distributed evenly on the gear, timing belts, and two motors. The structure of the lifting mechanism is similar to that of the lifting mechanism of the slidable platform of the locomotion mechanism. The lead screw is shared by two lifting mechanisms.

IV. CONTROL SYSTEM DESIGN

A. Configuration of Control System

The robot presented in this paper works in hard-to-reach locations and the working environment is complicated. Besides, the cleaning process is complex as the robot should perform a lot of actions with strict order. Thus, the robot should be able to perform cleaning task automatically. Moreover, the operator should be able to control the robot manually when some unexpected circumstances occur. Supervisory control is implemented to control the robot.

The control system of the insulator cleaning robot is comprised of the local controller and the ground control station, as shown in Fig. 9. Data and commands are transmitted between the local controller and the ground control station via Zigbee modules. The video image acquired by the local controller is transmitted to the ground control station and then displayed on the screen of the video displaying subsystem of the ground control station. The local controller is intended to control the motion of the robot, acquire and transmit images, receive and transfer commands, and manage power. The ground control station is able to accept the commands given by the operator, receive and display images on the screen, transmit and receive commands, and monitor the status of the control system. The control system works under supervisory control, and the local controller directly controls the robot and plans the motion of the robot while the ground control station monitors the execution process.

B. Hardware Design

The hardware of the control system is based on the TMS320F28335 Digital Signal Controller (DSC). This specific DSP includes plentiful peripherals such as enhanced PWM modules, enhanced quadrature encoder modules and serial communications interface modules.
The printed circuit board of the ground control station contains the voltage regulating unit, the keyboard interface, the serial communication interfaces and the relay driver interface. Fig. 10(a) shows the block diagram of the ground control station. The commands given by the operator can be accepted through the buttons of the keyboard. The status of the robot and prompt information is displayed on the liquid crystal display (LCM). Commands and data are transmitted via the Zigbee module which communicates with the controller via serial communication interface. The video transmitted by the local controller can be received and displayed on the monitor. Relays are used to switch the power of the video receiving and displaying subsystem to save energy when video information is not needed.

Fig. 10(b) shows the block diagram of the local controller. The local controller mainly includes the voltage regulating unit, the motor drive unit, the data transmitting unit, the video transmitting unit, the sensor unit, and the current sensing circuit. The motors of the grasping mechanism are driven by the motion controller and the other four motors are drive by integrated circuits. The data transmitting unit receives commands from the ground control station and sends frames via the Zigbee module. The images are captured by the cameras mounted on the robot and sent to the ground control station by the video transmitting unit. The sensor unit mainly deals with different sensors such as switches and encoders. The current of the motors is acquired through the current sensor circuit.

The printed circuit board of the local controller is developed, as shown in Fig. 11(a). Fig. 11(b) is the prototype of the ground control station.

C. Software Design

The program can be generated and debugged in C/C++ language using Code Composer Studio (CCS) developed by the manufacturer. The application software of the robot is composed of the software of the ground control station and the software of local controller, as shown in Fig. 12. The former scans and decodes the input of the keyboard, generates the commands, monitors the robot, sends commands to the local controller, receives and explains the frame from the local controller, and displays the status of the robot on the LCM. The latter receives the commands and data sent by the ground control station, sends frames to the station, plans the motion of the robot, controls the motors of the robot, deals with the sensors, and monitors the status of the robot.
The software of the robot system is implemented in the embedded control system using SYS/BIOS designed for applications requiring real-time scheduling. Synchronization modules and threading modules such as hardware interrupts and tasks are used. Table I shows the threads of the ground control station and their priorities. The threads of the local controller are listed in Table II.

<table>
<thead>
<tr>
<th>Thread Name</th>
<th>Description</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>TxDataDispose</td>
<td>sending data to local controller</td>
<td>4</td>
</tr>
<tr>
<td>RxDataDispose</td>
<td>receiving and disposing data sent by local controller</td>
<td>4</td>
</tr>
<tr>
<td>MotionPlan</td>
<td>making decision and plan motion</td>
<td>3</td>
</tr>
<tr>
<td>ScanKey</td>
<td>scanning and decoding the inputs from keyboard</td>
<td>2</td>
</tr>
<tr>
<td>SendDataToLCM</td>
<td>sending frame to the buffer of LCM</td>
<td>1</td>
</tr>
<tr>
<td>UpdateLCM</td>
<td>updating the display of LCM</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thread Name</th>
<th>Description</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>TxDataDispose</td>
<td>sending data to ground control station</td>
<td>3</td>
</tr>
<tr>
<td>RxDataDispose</td>
<td>receiving and disposing data sent by ground control station</td>
<td>3</td>
</tr>
<tr>
<td>FsmTick</td>
<td>determining the action and next status of robot</td>
<td>2</td>
</tr>
<tr>
<td>ExecuteAction</td>
<td>performing the specific action</td>
<td>2</td>
</tr>
<tr>
<td>HumanControl</td>
<td>disposing unexpected circumstances by operator</td>
<td>2</td>
</tr>
<tr>
<td>UpdateFsm</td>
<td>updating FSM model of robot</td>
<td>2</td>
</tr>
<tr>
<td>GetStatus</td>
<td>getting status of sensors and motors</td>
<td>1</td>
</tr>
</tbody>
</table>

D. Motion Planning Algorithm

Among the application software, the motion planning algorithm plays the most important role in controlling the robot. It first describes the given cleaning task and then generates the specific commands the robot should perform in a specific order to carry out the task. The workflow of the cleaning task is shown in Fig. 13, and the cleaning task mainly includes three subtasks, namely, the cleaning subtask, the downward movement subtask and the upward movement subtask. The cleaning subtask is intended to clean an insulator disc and the movement subtask is designed to move along the insulator string for a distance which equals the shed spacing of the insulator.

The motion planning algorithm is mainly consisted of two parts, namely, task description and decomposition, and generating and executing commands. After the operator presses the start button on the keyboard of the ground control station, the algorithm first decomposes the cleaning task into a sequence of subtasks. The cleaning task can be finished by performing the subtasks with a particular order. Due to the locomotion principle of the proposed insulator cleaning robot and the structure characteristics of the suspension insulator string, the robot should perform a sequence of actions to accomplish the subtask. For example, the robot should perform six actions in the given order to move downward along the insulator string. Finite State Machine is one of the common ways of representing how a sequence of behaviors should unfold [21], and is used to coordinate the actions of the subtasks. A state table containing actions for transitions is used to determine the actions the robot should perform, and then the actions are executed under the supervision of the local controller. Fig.14 shows the schematic diagram of the motion planning algorithm. The decision-making logic is intended to choose the Finite State Machine according to the subtask.

V. SIMULATION AND EXPERIMENTS

A. Simulation

The motion planning model is established in Matlab/Stateflow to validate the motion planning algorithm. Stateflow is a powerful tool to represent the event-driven system which makes a transition from one state to another when the condition is true. The Finite State Machine models are established, the events and data are defined, the decision-making logic is implemented, and finally the motion planning algorithm is tested. Fig. 15(a) is motion planning model, Fig. 15(b) is the Finite State Machine model of the downward movement subtask, Fig. 15(c) is the Finite State Machine model of the upward movement subtask.
Machine model of the cleaning subtask, and Fig. 15(d) is the decision-making logic of the motion planning algorithm.

The motion curve during performing the cleaning task is generated in Matlab and shown in Fig. 16. The basic trajectory of the joints is linear segments with parabolic blends [22]. The figure includes two sections. The section labeled with ‘I’ is the motion curves of the downward movement subtask, and the section labeled with ‘II’ is the motion curves of the cleaning subtask.

Simulation results show the model of the motion planning algorithm is correct. The sequence of actions generated by the model can be applied to robot control.

B. Experiments

The prototype of the insulator cleaning robot system is developed, as seen in Fig. 17. The robot system is consisted of the insulator cleaning robot and the ground control station.

The robot was installed on the insulator string which is composed of the double umbrella type porcelain insulator used in 500kV power transmission lines. The number of discs of the insulator string was set using the ground control station and the start command was given. The robot automatically performed the cleaning task. Fig. 18 shows the key states when the robot moved downwards along the suspension insulator chain for a particular distance which equals the spacing of the insulator.
When the robot was installed on the insulator set, the grippers of the robot engaged the cap of the insulators and the distance between the slidable and the fixed platform was the shed spacing of the insulator, as can be seen in Fig. 18(a). Then the grippers of the fixed platform moved to its open position, as shown in Fig. 18(b). The slidable platform was driven to the position where the distance between the slidable and the fixed platforms is the shed spacing of the insulator, as seen in Fig. 18(c). The grippers of the fixed platform then engaged the insulator, as can be seen in Fig. 18(d). The grippers of the slidable platform moved to its open position, as seen in Fig. 18(e). The slidable platform was driven to the position where the distance between the slidable and the fixed platform is the shed spacing of the insulator, as seen in Fig. 18(f). Finally, the grippers of the slidable platform engaged the insulator, as can be seen in Fig. 18(g). The robot finished downward movement along an insulator.

The upward movement process of the robot is quite similar to the down movement process and is tested. For simplicity, the details are not given. The cleaning process of a piece of insulator is also tested and the details of the process are not given here.

Experimental results show the motion planning algorithm is valid, and the robot is able to move along the insulator string and perform the cleaning task.

VI. SUMMARY

A live-line insulator cleaning robot is developed in this paper to remove the pollutants on the surfaces of the double umbrella type porcelain insulators for suspension insulator strings. The robot is consisted of the inchworm-based locomotion mechanism and the cleaning mechanism. The contaminated surfaces of the insulators can be cleaned by three rotating brushes. The robot can adapt to the changes of dimensions of the insulator in a certain range. The control system which is comprised of the local controller for direct controlling of the robot and the ground control station for supervision is implemented. The motion planning algorithm is introduced and implemented in C language. Simulation results verify the correctness of the motion planning algorithm. Preliminary experiments in the laboratory prove the validity and the feasibility of the insulator cleaning robot.

The future work should be oriented towards optimizing the structure and the parameters of the robot, testing the electromagnetic compatibility of the control system, conducting more laboratory experiments, and carrying out field experiments. Finally, the robot should be applied to performing live-line insulator cleaning task.

ACKNOWLEDGMENT

This work was supported by Science and Technology Projects of the State Grid Corporation of China (Grant no. Y2V3140301) and National Natural Science Foundation of China (Grant no. 51405482).

REFERENCES
