Behavior Control of an Automatic Inspection Robot for Insulators

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Abstract. This paper presents an automatic inspection robot for insulators installed on 500kV power transmission lines. In order to detect the poor insulators automatically, the robot’s behaviors are analyzed, and a behavior control model based on Finite State Machine (FSM) is established. Moreover, an exception handling method is proposed based on sensors and timers. The results of experiments in the laboratory prove that the control methods mentioned above are correct and valid. Experiments on a 500kV transmission live line show that the inspection robot can not only automatically move along the double insulator strings with variable intervals, but also reliably handle the abnormal conditions including slipping, power shortage, deadlocking, sensor abnormality, and probe loosening.

Introduction

Insulators are a kind of isolators connecting EHV power transmission lines with strain towers. They must have excellent mechanical and insulating properties. The insulator strings of the power transmission lines usually work under high voltage (110kV to 500kV) with being corroded by open-pit environment. The insulating properties of insulators probably become worse. These poor insulators are accident threat to the reliability of grid system. The detection of poor insulators has been paid close attentions by the power transmission departments.

At present, the exact inspection for insulators on high-voltage transmission lines usually uses contact inspection methods. Because these methods need the workers to climb up the strain towers, there are a lot of disadvantages, for example, high labor strength, low safety for the workers, and power cut. Because of these disadvantages, researchers has paid a lot of attentions to develop some robots to replace the workers, for example, the poor insulator inspection robot from Japan's Sumitomo Machinery Company [1], the suspension insulator detection robot from Hydro-Quebec of Canada [2], and the automatic inspection robot for live-line insulators from Electric Power Research Institute of Korea [3]-[5]. This paper presents an automatic inspection robot for insulators, and proposes its behavior control model based on FSM. The robot can move along the double insulator strings of strain towers and adapt the variable interval between strings automatically. It also can measure the insulator resistance automatically using its smart insulator detector and send the data to PC for subsequent analysis by ground-workers.

The paper is organized as follows: After the introduction, Section II describes the structure of the robot system, including the mechanical structure, and the control system structure. Section III sets up the behavior control model of the robot. Section IV gives the experimental analysis and results. Conclusion is drawn in Section V.
Description of the Robot System

The insulator detection robot is composed of two track wheels, two guide frames and one body, as shown in Fig.1 (details in [6]). The track wheels are driven by two DC motors and both connected to a variable-pitch mechanism. With the variable-pitch mechanism, the robot can adapt to the double insulator strings with variable intervals automatically. There is a self-contained embedded control system and an insulator detector in the body of the detection robot. When the robot works, the workers put it on the beginning of the double insulator strings of strain tower. The robot can move along the double insulator strings and adapt the variable intervals of insulator strings automatically. It also can measure the insulator resistance automatically using its smart insulator detector. When it arrives at the end of the double insulator strings, it can move back to the initial position automatically.

The robot has a multi-sensors system that consists of position sensors, angle sensors, voltage sensors, current sensors, and encoders. The position sensors sense the position of insulators, the end and initial position of the insulator strings. The angle sensors and current sensors detect the touch information between the probe and insulators. The voltage sensor measures the voltage of the battery. The speed of motors is measured by the encoders.

![Fig.1 The insulator detection robot](image1)

![Fig.2 The working inspector](image2)

Behavior Control of the Robot

Behavior Analysis of the Robot

The insulator inspection robot imitates the behaviors of power line inspectors. The inspector working on the insulator strings is shown in Fig.2. The inspector moves astride along the double insulator strings of strain tower, and stops to inspect the insulators when he arrives at the suitable position. After finishing inspecting a couple of insulators, the inspector moves on to the next couple of insulators to inspect them. When the inspector detected the whole insulator strings, it moves back to the beginning. The behavior patterns of the working inspector include stopping, going ahead, inspecting, and going back. This four behavior patterns are described briefly as follows:

Stopping: A behavior of the inspector stopping on the insulator strings.

Going ahead: A behavior of the inspector moving along the insulator strings to the suitable position of next inspector.

Inspecting: A behavior of the inspector stopping to inspect the resistance of insulators and memorizing the results.

Going back: A behavior of the inspector going back to the strain tower.

According to the behavior patterns of the inspector, the inspection robot will have 7 behavior patterns: setting, stopping, going ahead, probe moving, inspecting, probe returning, and going back.
Behavior Control Modeling of the Robot

Finite State Machine (FSM) consists of the finite states and the transfers between them. Its working principle can be described as: in the range of a nonempty finite states, the robot transfers from a state to another according to certain mapping rules when an input event occurs [7, 8].

The behavior model based on FSM of the insulator inspection robot can be expressed as Eq.1.

\[
M = (Q, \Omega, \delta, q_0, F)
\]

where \( Q \) is the set of finite states of the robot, \( q_i \) is one state of \( Q \). \( \Omega \) is the set of inputs of the robot. \( q_0 \in Q \) is the original state of the robot. \( F \) is the final state of the robot. The function of state transfer is \( \delta : Q \times \Omega \rightarrow Q \), then \( \delta(q_i, a) = q_j \) means that the robot transfers from the state \( q_i \) to \( q_j \) when the input is \( a \) ( \( a \in \Omega \)).

First, the definitions of the states and input events for the robot should be described. The states of the robot include initial, setting, stopping, going-ahead, probe moving, inspecting, probe returning, and going-back.

Initial state (\( q_0 \)): The robot controller sets its parameters in this state.

Stopping state (\( q_1 \)): The right and left motors, and the probe motor stop. The keyboard is unusable.

Going-ahead state (\( q_2 \)): The right and left motors run forward with the probe in the initial position.

Probe moving state (\( q_3 \)): The probe moves away from the initial position.

Inspecting state (\( q_4 \)): The robot inspects the insulators.

Probe returning state (\( q_5 \)): The probe returns to the initial position.

Going-back state (\( q_6 \)): The right and the left motors run backward.

Setting state (\( q_7 \)): The keyboard is usable.

The input events of FSM are decided by the information of the switch and sensors installed on the robot. Relational switch and sensors include a setting switch, four position sensors, an angle sensor, a counter for inspection, and a current sensor. The input events \( A \) can be expressed as Eq.2.

\[
A = f (S)
\]

where \( S = [s_1, ..., s_n] \), \( s_i \) is the state of the \( i \)th sensor or switch.

Define the forward of the robot as the positive direction. \( s_1, s_2, s_3, s_4 \) are the position sensors of the front left, rear left, front right, and rear right respectively; \( s_5 \) is the current sensor; \( s_6 \) is the counter; \( s_7 \) is the angle sensor. \( s_8 \) is the setting switch. Restricted by the operation mode of the robot, the right and left position sensors can’t be used together.

Definitions of the input events:

\( s_8 \) is closed (the input event \( a_0 \)), which indicates that the robot needn’t be set. \( s_8 \) is opened (\( a_i \)), which indicates that the robot need set; \( s_1 / s_3 \) and \( s_2 / s_4 \) arrive at their positions synchronously (\( a_2 \)), which indicates that the robot arrives at the suitable position to inspect the insulator; \( s_1 / s_3 \) does not arrive at its position, \( s_2 / s_4 \) arrives at its position (\( a_1 \)), which indicates that the robot arrives at the end of the insulator strings; \( s_1 / s_3 \) arrives at its position, but \( s_2 / s_4 \) doesn’t arrive at its position (\( a_4 \)), which indicates that the robot arrives at the initial position of the insulator strings; \( s_5 \) is not in its initial position, and \( s_5 \) is greater than the value \( I_{\text{max}} \) (\( a_5 \)), which indicates that the probe arrives at its suitable position to detect the insulator; \( s_5 \) arrives at its initial position, and \( s_5 \) is under the value \( I_{\text{max}} \) (\( a_6 \)), which indicates that the probe arrives at its initial position; The counter for inspection \( s_6 \) adds 1(\( a_7 \)), which indicates that the inspection finished; The initialization of the robot is finished (\( a_8 \)).
According to the definitions of the states and the input events, the behavior model of the inspection robot is shown in Fig. 3.

![Behavior model of the robot](image1)

![Behavior model with exception handling](image2)

**Behavior Modeling of the Robot with Exception Handling**

Some exceptional states may occur when the robot is working, for example, power failure or power shortage, slipping, deadlocking, sensor abnormality, and probe loosening. These exceptional states must be diagnosed and handled timely to avoid the damage to the power grids and the robot [8]. The exception states and exception input events are added in the established model.

$q_8$ is defined as the exceptional state. In the state, the robot finishes the initialization of the probe, and moves back to the initial position of the insulator strings.

The robot diagnoses the exceptions based on the sensors and timers. The exception input events $A_{abn}$ can be expressed as Eq. 3.

$$A_{abn} = f_{abn}(S, T)$$

where $T = [t_1, ..., t_m]$ is the set of the time constants.

Some exceptional events are defined as follows:

The setting of the speed is not 0, but the output of $s_{10}/s_{11}$ is 0, and $s_1, s_2, s_3, s_4$ are changeless in the period of time $t_1$ ($a_9/a_11$), which indicates that the left/right wheel is deadlocked; If $s_1, s_2, s_3, s_4$ are changed in the period of time $t_1$ ($a_{10}/a_{12}$), which indicates that the left/right encoder $s_{10}/s_{11}$ is in faults.

$s_{10}$ and $s_{11}$ is not 0, the count of a position sensor arriving its position is 0 in the period of time $t_2$, but others’ counts are same (>0) ($a_{13}$), which indicates that the position sensor is in faults.

$s_{10}$ and $s_{11}$ is not 0, the count of every position sensor arriving its position is 0 in the period of time $t_3$ ($a_{14}$), which indicates that the robot tracks are slipping.

In the period of time $t_4$, the angle sensor $s_7$ is greater than its set value $\theta_{\text{max}}$, but $s_5$ is under its set value $\text{I}_{\text{max}}$ ($a_{15}$), which indicates that the probe is loosening.

According to the definitions of the exception states and the exception input events, the set of exception input events $\Omega_{abn} = \{a_9, a_{10}, a_{11}, a_{12}, a_{13}, a_{14}, a_{15}, a_{16}\}$. When the input event $a_m \in \Omega_{abn}$, the robot’s state is transferred to the exception state $q_8$.

The behavior model of the inspection robot with exception handling is shown in Fig. 4. Where $\Omega_{abn} = \{a_9, a_{10}, a_{11}, a_{12}, a_{13}, a_{14}, a_{15}\}$.
Experiments

In order to verify the functions of the robot, some experiments are carried out in the laboratory, as shown in Fig.5. Without any exceptional states, the robot can move steadily from the start of the insulator strings built in the laboratory to the other end, and detect the insulators one by one. The robot can move back to the start autonomously when it arrived at the other end. If the robot is held up by blocks when it is moving, it will begin slipping. After 10 seconds, the robot will handle the exceptional state to move back to the start. After continuously working about 9 hours, the robot will be in the exceptional state of power shortage when the voltage of the battery is under the set value $V$ and move back to the start. In addition, the main technical specifications of the robot are as follows: Weight, 13kg; Dimensions, 920×550×400mm; Slope climbing angle, 15°; Testing period, 2 strings/30min.

![Fig.5 Experiments in the laboratory](image1)

Experiments are implemented on a 500kV transmission live line, as shown in Fig.6. The results of the experiment show that: the insulator detection robot works very well in the 500kV extra-high voltage environment; the robot can autonomously detect the insulator one by one; the control method of the robot is valid and reasonable and has the capability of handling abnormal conditions including slipping, power shortage, deadlocking, sensor abnormality, and probe loosening; the hardware and the software of the system are stable and reliable; the insulator detection robot has the ability to replace human to implement the insulator string detection.

![Fig.6 The experiments on the 500kV transmission live line](image2)

Conclusion

This paper introduces an automatic inspection robot for insulators and its behavior control method. A behavior control model based on Finite State Machine (FSM) is established by imitating workers, and an exception handling model is proposed based on sensors and timers. Mary experiments have been implemented and the results prove that the robot can steadily move along the double insulator strings with variable intervals, and move back to the end connected with the tower automatically when the robot is in the abnormal states, such as slipping, power shortage, deadlocking, sensor abnormality, and probe loosening.
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