Path Planning for Power Transmission Line Inspection Robot Based on Visual Obstacle Detection

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Abstract—In this paper an autonomous mobile robot is proposed for inspecting power transmission lines in mountainous regions. After a brief introduction of background and the robot mechanism, the key functionalities of the inspection robot—obstacle detection in traveling, path planning in obstacle crossing and large-angle line climbing, are discussed in detail. Obstacles are detected and recognized efficiently by a visual method. The obstacle description is built based on visual obstacle detection and a feasible obstacle crossing path is found using a visual graph algorithm. Finally, some field experiments are carried out to show that the robot can work well on the power transmission lines in mountainous regions with the aforementioned functionalities.

I. INTRODUCTION

The electric power supply is becoming increasingly important for our society. In order to keep power transmission lines reliable and minimize the loss when the power supply fails, the transmission lines should be inspected regularly to obtain running conditions and find transmission line faults as early as possible. This inspection task is carried out commonly by two methods: foot patrol and helicopter-assisted inspection [1]. In the foot patrol inspection, a team of workers drive or walk from tower to tower, and inspect the power transmission lines with help of binoculars and infrared cameras on the ground. Sometimes, workers have to climb the tower and ride a gondolas suspended on the overhead ground wires [2]. The foot patrol inspection method can find the faults of the surface of power transmission line equipments with high accuracy but there are many disadvantages, e.g. long inspection cycle, high working intensity and risk for workers [3]. Helicopter-assisted inspection method is highly efficient comparing to foot patrol inspection. In the method, the helicopter is flown over the power transmission lines with a video camera filming the conditions of the power lines. The video are then inspected manually by the power grid experts in the office. This method is faster than the foot patrol method but more expensive, more climate-depending and usually less accurate.

The mobile robots applied to inspect power transmission lines have been developed since the early 1990s [4-8]. The robots are autonomous or semi-autonomous, which replace people or assist people in inspecting power transmission lines. Commonly, the robots walk on the power transmission line using a wheeled trolley and cross obstacles using additional devices, e.g. leg-gripper structures. The application of autonomous mobile robots for power transmission line inspection can achieve better inspection accuracy and better price performance than helicopter-assisted inspection, and is safer, less tedious and much faster than foot patrol inspection.

Up to now, the mobile robots for power transmission line inspection have been researched for ages and some robot prototypes have been developed. However, there are still lots of key techniques needed to be settled for the practical application, e.g. automation for obstacle detecting and crossing, adaptability for grids in mountainous regions, and mechanism optimal design.

This paper focuses on inspection robots’ automation for obstacle detecting and crossing. An obstacle detection and classification method is proposed in [9], which is based on several arrays of ultrasonic proximity sensors. A method based on images captured on transmission lines can recognize counterweight and clamp using the structure-constrained feature in [10][11]. UTM-30LX LIDAR system is used for obstacle detection and location in [12]. These methods were tested successfully in experiments. However, they require considerable computing power, which is not sufficed by the onboard CPU of the inspection robot. Another necessary capability for inspection robots is autonomous obstacle crossing. A self-navigated inspection robot is presented in [14], where the obstacle crossing is executed as a set of pre-programmed steps for only known obstacles on the transmission lines. The inspection robot in [15] performs a fuzzy control algorithm for obstacle negotiation. An expert system is proposed in [16] for an autonomously obstacle-negotiation inspection robot for extra-high voltage power transmission lines. The expert system combines basic movements based on rules to cross known obstacles. These aforementioned robots perform path planning in obstacle crossing as a sequence of pre-programmed steps and their paths for obstacle crossing are usually not smooth and not the shortest.

Most aforementioned robot prototypes have carried out the field experiments on the even lines, where the robots needn’t climb large-angle lines. This paper presents an autonomous inspection robot designed for the power transmission in mountainous regions. The functionalities of autonomous traveling, autonomous obstacle crossing and large-angle wire climbing are achieved for the robot. The remaining of this paper is organized as follows: The background and robot design are presented in Section II. Section III discusses the method of obstacle detection in traveling, path planning in
obstacle crossing and large-angle wire climbing. Finally, Section IV gives the experimental results on power transmission live lines from a straight line tower to a tension tower in mountainous regions.

II. INSPECTION ROBOT DESCRIPTION

A. Background

The environment of power transmission lines is quite complicated: consisting of tension towers (TT), straight line towers (SLT), power transmission lines (PTL), overhead ground wires (OGW), and other electric power equipment, e.g. counterweight, clamp, spacer, clevis & tongue. In the foot patrol inspection, workers drive or walk from tower to tower and inspect the power transmission lines with help of binoculars and infrared cameras. Inspection tasks mainly focus on the faults of the grid (the transmission lines, the power towers and their foundations, the fittings and the insulators) and the environment along it (trees, quarries, buildings etc.)[8]. This work is slow, tedious, and risky for the workers. Especially when the grid is in mountainous region, as shown in Fig.1, workers have to walk up hill and dale to inspect the power transmission lines along the route on foot. There are great advantages using inspection robots for the power line inspection in mountainous region. Inspection robots can roll along OGW, get around the obstacles on the OGW, and inspect the lines. Workers only need to install the inspection robot on the OGW at the tower 1#, drive it to the tower 6# and retrieve it. However, there are some differences between the robot in mountainous region and the other ones. The functionalities of the robot in mountainous region should include not only autonomous traveling along the OGW, autonomous inspection, and at least semi-autonomous obstacle crossing [1], but also passing through the narrow space between OGW and SLT, and climbing on large-angle OGW when the robot cannot roll up.

Fig. 1. Environment of power transmission lines in mountainous region.

B. Robot Design

The functionalities mentioned in the background require a complex mechanism for the inspection robot. Perhaps, the bionic principles can help the robot’s design. Monkeys are good at climbing on the cable or between branches, as shown in Fig.2. They can move flexibly by swinging their arms from branch to branch, called brachiation, and can pass narrow space by hanging themselves close to the cable to reduce their heights, as shown in Fig.2 (f). When brachiating, the two powerful and flexible arms of monkey play a key role, and the crura keep the body balanced. The arm has a claw for grasping, rotary joints respectively for wrist, elbow, and shoulder. Hence, the inspection robots can be designed by bio-brachiation to fulfill the actions of monkeys, e.g. climbing on large-angle OGW and crossing obstacles by brachiating, passing narrow spaces, and grasping.

Fig. 2. Actions of monkeys.

The bio-mimetic inspection robot and its mechanical system sketch are shown in Fig.3. The robot consists of two arms, two worm and worm gear mechanisms, and two control boxes. Each arm(Fig.3 (1)) has a wheel for rolling along the lines, a claw(Fig.3 (2)) for grasping objects, two rotary joints (Fig.3 (3, 5)) respectively for pitching the wrist and rotating the wheel-claw mechanism, and a prismatic joint (Fig.3 (4)) for driving the arm upward and downward. The worm and worm gear mechanism (Fig.3 (5)) drives the arm forward and backward to keep the robot balanced and adjusts the distance between arms. The control system and the inspection devices are arranged in two control boxes which are installed on the both ends of the robot instead of being suspended under the body, thus to reduce the robot’s height.

Fig. 3. Mechanical system sketch of the robot.

The inspection robot rolls along the OGW with its wheels, crosses obstacles and climbs large-angle OGW by the bio-brachiation as monkeys, as shown in Fig.4. The process of the bio-brachiation of the robot is given as follows: Fig.4 (a): the gripper of the rear arm is released from the OGW; Fig.4 (b): the rear arm retracts until it is lower than the OGW; Fig.4 (c-d): the robot brachiates until the rear arm crosses the
obstacle; Fig. 4 (e): the unattached gripper is re-attached to the OGW; The similar process will be executed for the other arm to achieve the bio-brachiation.

III. KEY TECHNOLOGIES OF THE INSPECTION ROBOT

The study of the inspection robot for power transmission lines in mountainous region focuses on the functionalities of autonomous traveling, inspection, and at least semi-autonomous obstacle crossing and large-angle wire climbing. Hence, the obstacle detection and the path planning in obstacle crossing and large-angle wire climbing are the key technologies.

A. Obstacle Detection in Traveling

The obstacle detection and recognition in traveling is the first step for the inspection robot to travel along the line and to cross obstacles autonomously. Some methods were proposed in [9-12]. These methods require considerable computing power, which is not sufficed by the onboard CPU of the inspection robot. A new method with good computing speed is needed for the inspection robot to detect and recognize obstacles autonomously.

The OGW where the inspection robot travels is a semi-structured environment, where counterweights and clamps limited in the region of OGW are the main obstacles. The inspection robot in this paper detects and recognizes obstacles by its camera installed in the front, as shown in Fig. 5. OGWs are cables with aluminum strands on the outer layers. A sudden diameter change will be detected in the image from the camera when an obstacle is present. In order to extract the change (exceeding a given threshold), images from the camera are processed by image segmentation based on gray and by boundary measurement with Hough Transform which can detect the straight edges of the OGW. Then, the center of the OGW can be extracted with adding the detected edges, and the diameters of the objects around the center can be calculated, as shown in Fig. 6 (a).

\[ D_i = H_i - L_i \]  

Fig. 6 (b) shows the change of \( H, L, \text{ and } D \) for OGW with counterweight. \( H \) is the width from the upper edge to the center of the object, and \( L \) is the width from the center to the lower edge. The diameter \( D \) is defined as:

\[ S = \sum_{i \in \{A,B\}} \frac{H_i}{L_i} \]  

\( S = 1 \): the obstacle is a known obstacle (counterweights or clamps), otherwise it is an unknown obstacle.

The other features used to recognize obstacles are the length \( (B-A) \) and average width \( (\sum_{i \in \{A,B\}} D_i/(B-A)) \) of the
obstacle. By the application of the aforementioned features, obstacles can be classified using the method of Support Vector Machine [13].

B. Path Planning in Obstacle Crossing and Large-angle Wire Climbing

Path planning is a necessary capability for an inspection robot capable of autonomously travelling along the OGW. The robots mentioned in [14-16] perform path planning in obstacle crossing for known obstacles as a set of pre-programmed steps, and their paths for obstacle crossing are usually not smooth and not the shortest. An obstacle avoidance trajectory planning based on the Lazy Theta* algorithm is presented for both known and unknown obstacles in [17]. In order to minimize energy consumption and obstacle crossing time, the inspection robot presented in this paper executes shortest, smooth, and coordinated obstacle crossing paths.

For the purpose of path planning in autonomous obstacle crossing and large-angle wire climbing, the immediate workspace environment of the robot is represented using rectangles. For known obstacles (classified by the aforementioned method), these obstacles with pre-calculated sizes can be described using rectangles in 2D vertical map. For unknown obstacles, these obstacles must be described in 2D horizontal map using rectangles sized by the image process mentioned above.

As shown in Fig.7, obstacles descriptions for both known (e.g. counterweights) and unknown ones are presented as examples. The inner rectangles appropriately enclose the entire obstacles, and the outer ones over-bound the obstacles in order to take the size of the robot parts into account (mainly the moving gripper). The grippers are described as cubes simply. They are considered points which are correspond to the 'centre' of grippers in path planning. In view of the sizes of the grippers, the inner rectangle is enlarged by 6cm around it to avoid the collision between grippers and obstacles. The use of rectangles for obstacles descriptions will allow the robot to plan its paths more simply and efficiently from one side of the obstacle to the other along the OGW.

![Fig. 7. The obstacle descriptions for counterweights and unknown obstacles.](image)

The robot travels along the OGW by rolling the wheels of both grippers. If an obstacle is detected, the robot must plan paths for both grippers to avoid the obstacle described with rectangles. In order to create two shortest paths (one for the front gripper and one for the rear), a visual graph algorithm is presented. In the algorithm, the initial waypoint, the final waypoint, and all the nodes of the rectangles describing obstacles are connected to create line segments. If a line segment does not intersect with obstacles, it is reserved as a visual line segment. Otherwise, it is deleted as an invisible one. As shown in Fig.8, node S and G are the initial and final waypoint, nodes Ni are the nodes of the rectangles describing obstacles. The visual line segments, e.g. SN1, N1N2, N1N7, etc, form a visual graph. The invisible line segments, e.g. SN3, N1N6, SN8, etc, are deleted, which are determined as:

\[
x \geq \min(x_i) \land x \leq \max(x_i) \land y \geq \min(y_i) \land y \leq \max(y_i)
\]

(3)

Where, \((x_i, y_i)\) is the node of the rectangles describing obstacles, and \((x, y)\) is the intersection of obstacle edges and undetermined line segments. Due to the mechanical designs of the robot, the line segments intersecting the line SG is undesired, e.g. N3N6, N1N2, N1N4, N5N6, and N7N8, which should be deleted. The desired path is the shortest path of the paths consisting of visual line segments from S to G as shown in Fig.8.

![Fig. 8. Path planning based on visual graph algorithm.](image)

The chosen paths in obstacle crossing and large-angle wire climbing are shown in Fig.9. For known obstacles, the robot crosses the obstacles by the method mentioned in Fig.4, and its paths are shown in Fig.9 (a-b) for clamps, and large-angle wire. For unknown obstacles, which are described in 2D horizontal map, the robot releases its front gripper, moves it around the obstacle horizontally, and re-attaches it to the wire, as shown in Fig.9(c). A similar procedure is executed for the other gripper.

![Fig. 9. Chosen paths in obstacle crossing and large-angle wire climbing.](image)

IV. EXPERIMENTS

The prototype of the inspection robot is designed and some field experiments are carried out on power transmission lines in mountainous regions, as shown in Fig.10. In the field
experiment, the robot is hung on the OGW firstly, as shown in Fig.10(b), and travels along the OGW from a straight line tower to a tension tower autonomously, detects and crosses the obstacles on the OGW (e.g., counterweights and clamps as shown in Fig.10(c)) with the aforementioned methods.

As shown in Fig.13, an example that the robot recognizes obstacles is given. The number of intersections of D and is 4, the symmetry S is 0.934, length (B-A) and average width \( \left( \sum_{i[A,B]} D_i / (B - A) \right) \) of the obstacle are 186 and 110.149. By the application of the features, this obstacle can be classified into counterweights.

In the field experiment, the robot crosses the obstacles autonomously. For the known obstacles, the robot performs the bio-brachiation actions in 2D vertical map. Some video images of the main steps of the robot crossing counterweights and clamps are shown in Fig.14 (a-c). For the unknown obstacles, the robot plans the path to cross them in 2D horizontal map. An obstacle crossing example of unknown one is given in detail. A video image of the environment around the robot’s front gripper is shown in Fig.14 (d). The rectangle describes the obstacle and the line segments show the expected gripper path. Fig.14 (e-f) show the main steps of the unknown obstacle crossing for the front gripper. The robot follows the expected gripper path and successfully achieves the correct end location on the other side of the obstacle. Lastly, the front gripper re-attaches to the OGW based on a feedback control using a vision system [18].

V. CONCLUSION

An inspection robot for power transmission lines in mountainous regions is presented in this paper. By imitating the actions of monkeys, the robot achieves the functionalities of autonomous traveling, autonomous obstacle crossing and large-angle wire climbing. With the application of the images from the camera installed in the front of the robot, the obstacles are detected and recognized efficiently. Using rectangle obstacle descriptions, a feasible obstacle crossing path is found based on a visual graph algorithm. Some field experiments were carried out, showing that the robot can cross representative obstacle (known and unknown) and travel...
autonomously along the OGW from a straight line tower to a tension tower in mountainous regions.

Future work should mainly be oriented toward immediate workspace environment modeling and path planning in 3D map, which are for more reliable obstacle detection and optimal obstacle crossing path.

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REFERENCES


