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Path Planning of Inspection Robot Based on 3D Scanning Information of Transmission Tower

Y. Jing and W. Zhang

**Department of Structural Engineering, Tongji University
Shanghai, China**

Abstract

Comprehensive, safe and efficient acquisition of structural information is of great significance in the field of intelligent inspection and evaluation of steel structures. In this paper, the structural information of the steel transmission tower was obtained through 3D laser scanning and other new surveying technologies. On this basis, the three-dimensional reverse reconstruction was carried out, and the related detection and evaluation work such as the overall slope measurement of the structure was carried out. The three-dimensional model of transmission tower was also established according to the obtained data such as node coordinates, node connection and rod length. This paper presents A path planning method for detection robot under the background of transmission tower, including two-point path planning based on A-star algorithm, designated multipoint path planning based on genetic algorithm and full coverage path planning based on spiral coverage method. It provides ideas and references for the future implementation of structure inspection with multi-source information and the production of relevant inspection robots in practical projects.

Keywords: transmission tower, safety assessment, inspection robot, path planning, A-star algorithm, genetic algorithm, point cloud, three-dimensional model.

1 Introduction

As the main support facilities for high-voltage transmission lines, the number of steel transmission towers is still increasing. Because the towers are exposed to the wild all year round, they will inevitably be exposed to the sun and rain. In the case of long service time or harsh environmental conditions, the towers may be corroded or deformed and other non-human phenomena, resulting in damage or even collapse of the towers [1]. However, there are a series of problems such as incomplete design data, unclear existing structure status and poor maintenance quality for the transmission towers in service [2]. Therefore, it is necessary to conduct a comprehensive evaluation of the transmission towers to determine whether the transmission towers can meet the requirements of safety and normal use.

In recent years, with the continuous update and development of various information acquisition devices, the means of obtaining structural data are becoming more and more abundant. For example, the emerging UAV photogrammetry [3], three-dimensional laser scanning technology [4] and other new surveying and mapping technologies can obtain geometric information of buildings without contact, and inspection robots [5,6] carry equipment for contact detection to obtain structural information such as building rust and material mechanical properties. These new detection methods have gradually become an important means to obtain building damage information and structural assessment. Therefore, this paper proposes to apply these new technical means in the field of intelligent inspection and evaluation of steel transmission towers with the purpose of solving the problems of long time, low efficiency, strong subjectivity and high risk of manual field inspection and investigation.

Among them, the engineering examples of damage detection and performance evaluation of various structural components by carrying various detection instruments by inspection robots are increasing year by year, and a variety of inspection robots are constantly appearing [7,8].

However, compared with other detection methods, the application of inspection robots is relatively in its infancy. In particular, the inspection robots used in the background of high-rise steel structures such as steel transmission towers still need to be developed, and there are few researches in related fields.

This paper took the steel transmission tower as the research object, and obtained the damage information of steel transmission tower by new means such as UAV oblique photography and 3D laser scanning. On this basis, a 3D model was established according to the obtained structure information. And a path planning method of inspection robot under the background of transmission tower was proposed.

2 Three-dimensional information acquisition and reverse modeling of transmission tower

The technical route of this work is as follows: First of all, the 3D design model was obtained by forward modeling according to the structural design drawings. Then the laser scanning technology was used to scan the target transmission tower, and a dense and highly accurate point cloud data was obtained by registration of multi-station scanning data. Then the three-dimensional solid model was obtained by reverse modeling of the point cloud data, and the three-dimensional solid model was compared with the previous three-dimensional design model to carry out deformation detection, three-dimensional measurement and other work. Finally, a 3D information model can be obtained, and each component has attribute labels.

2.1 Three-dimensional information acquisition

Paper The modeling was carried out according to the data of an in-service transmission tower. The scanning instrument was FARO 3D laser scanner, and the laser scanning principle diagram is shown in Figure 1. The principle is to collect the reflected data by emitting laser to the characteristic points of the target building and settle the three-dimensional spatial coordinate information of the characteristic points.

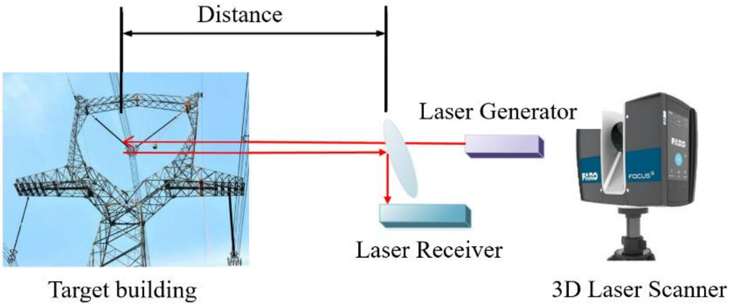
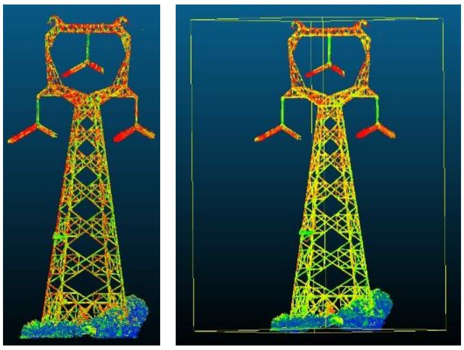


Figure 1: Schematic diagram of laser scanning

After getting the data information, a match between the information of different sites should be made. Because the single-site cloud has an independent coordinate system. In order to obtain the complete data of the object, it is necessary to convert the point cloud data under different view coordinate systems to the unified coordinate system. The algorithm [9] based on the Iterative Closest Point (ICP) method was adopted for point cloud registration and point cloud matching between different sites. Finally, the collected 3D laser scanning point cloud data and the 3D transmission tower model constructed according to the drawings are shown in Figure 2.

(a) Original point cloud data (b) Three-dimensional design model
Figure 2: Original point cloud data and 3D design model

Then there was the preprocessing of point cloud data, that was, based on certain mathematical models, the noise content of the data was reduced through relevant operations. And the redundancy of the data was simplified to improve the quality of point cloud data. As shown in Figure 3, we used Gaussian filtering algorithm to filter random noise in the data to improve the deterministic value.



(a) Original point cloud data (b) Filtered point cloud data
Figure 3: Preprocessing of point cloud data

2.1 Reverse modeling and data results

Afterwards, three-dimensional reconstruction was carried out to build a solid model through parametric fitting of the point cloud. The object of this study was the steel transmission tower, and the reference modeling method based on point cloud was adopted. In the modeling process, the compliance error between the point cloud and the model was taken into account, that was, the degree to which the model deviated from the point cloud was controlled. In this work, we chose the outermost point cloud for modeling.

In the deformation detection process of the transmission tower, the overall inclination of the structure and the deformation of the component were measured. Figure 4 shows the feature plane fitted by the data of one side of the tower. On the basis of the model correction, the overall inclination of the transmission tower could be obtained according to the plane normal information. This was a rapid detection of the overall slope of the building. Furthermore, on the basis of the existing design model or the previous model, the change of the structure during two or more measurements could also be analyzed for structural monitoring.

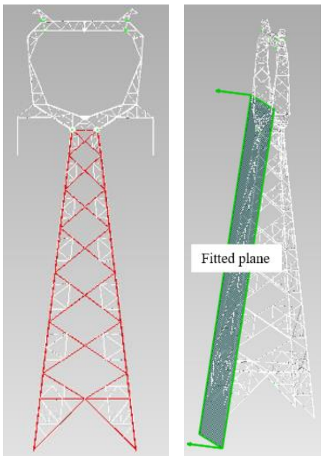


Figure 4: Overall inclination measurement of the structure

The bending degree of the rod between the main material nodes on the tower surface could also be calculated according to the node coordinate data. By comparing with the standard limit, the qualified and unqualified rods could be marked in the model with different information. Finally, the path planning of inspection robot was carried out based on the obtained information such as the three-dimensional coordinates of the transmission tower nodes, the connections between nodes and the length of the rods.

3 Algorithm theory of three-dimensional path planning for inspection robot

Path planning of mobile robot refers to finding a motion path from the given starting point to the target point or traversing all points in the working environment with obstacles. Meanwhile, the robot can safely and collision-free round all obstacles during movement, and find the shortest obstacle avoidance path under the condition of ensuring safety [10]. Path planning is a process of continuous interaction between robot and surrounding environment information. According to the degree of perception of surrounding environment information, robot path planning can be divided into global path planning with knowing all environment information and local path planning with knowing part of environment information. Besides, according to the coverage of the path, the path planning of the robot can be divided into point-to-point path planning and full-coverage path planning.

According to the actual engineering environment, comprehensive environmental information can be constructed if design drawings and other materials are available. If data miss, structural data can also be obtained by reverse modeling and other technologies through 3D laser scanning or UAV aerial photography. Therefore, our work belongs to the global path planning which knows all environmental information. It includes point-to-point path planning and full coverage path planning.

3.1 Point-to-point path planning

Point-to-point path planning is to find an optimal or sub-optimal path for autonomous obstacle avoidance from the starting point to the ending point in the work space, which requires less time and path consumption [11]. The algorithm can be divided into traditional path planning algorithm and intelligent path planning algorithm. Traditional path planning algorithms mainly include artificial potential field method, Dijkstra algorithm, A-star algorithm and so on. [12,13]. Intelligent path planning algorithms mainly include neural network algorithm, ant colony algorithm, genetic algorithm and so on. [14,15]. In this paper, the point-to-point path planning of the inspection robot was divided into two parts. One was the point-to-point path planning based on A-star algorithm, and the other was the designated multipoint path planning based on genetic algorithm.

3.1.1 A-star algorithm

A-star algorithm is a heuristic search algorithm, which searches in state space. It firstly evaluates each searched position to obtain the best position, and then searches from this position until reaching the target. It combines the advantages of Dijkstra's algorithm and Greedy best-First algorithm [16]. The principle can be shown by formula (1):

$$f(n) = g(n) + h(n) \tag{1}$$

Where f(n) is the estimated cost from the initial state through state n to the target state and g(n) is the actual cost from the initial state to state n in the state space. And h(n) is the estimated cost of the best path from state n to the target state, also known as the heuristic function. For the path search problem of inspecting robot, the states are the different nodes of the structure, and the cost is the distance between the nodes.

3.1.2 Travelling salesman problem

The A-star algorithm introduced above is only to find the shortest path between two points, but in the actual detection process of the transmission tower, the rods in different positions should be sampled, which becomes the path planning of the specified multiple points, involving the problem of sequencing and combination between different nodes. The mathematical model that conforms to this kind of problem is the Travelling salesman problem [17].

As shown in the figure 5, the problem is given a series of cities and the distances between different cities, and the traveler needs to visit each city once and return to the starting city. Eventually, it needs to solve the shortest loop.

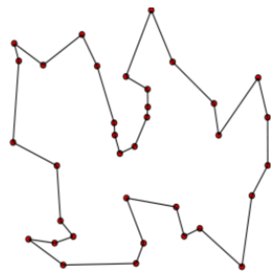


Figure 5: Schematic diagram of the traveling salesman problem

Its objective function is shown in equation (2), where v_i is the city number and $d(v_i, v_{i+1})$ represents the moving cost from city i to the next city, which can represent distance, time and so on.

$$f(V) = \min\left[\sum_{i=1}^{n-1} d(v_i, v_{i+1}) + d(v_n, v_1)\right] \tag{2}$$

Our idea was to treat the nodes of transmission tower as city points, and the distance between nodes is the distance between cities.

3.1.3 Genetic algorithm

There are also many algorithms used to solve the travelling salesman problem, and we chose genetic algorithm to solve it, because this algorithm starts from the string set of the solution of the problem, rather than from a single solution, which has a large coverage [18].

The background of genetic algorithm is to simulate the crossover and mutation of chromosome genes, so the main genetic operators are selection, crossover and mutation [19]. Explain the process in the context of the transmission tower. Each node has a number, then the first thing is coding, that is, the number of the target node is arranged in different order. As a result, the obtained different series of numbers are different solutions to the problem, that is, different paths. Secondly, it randomly generates a certain number of solutions which is called initializing the population, that is, a certain number of paths. After that, it is to evaluate the population by fitness function f(x), which is set as the reciprocal of the total path length V(x) in this problem, as shown in equation (3). The reason is that if the fitness function value becomes greater, the evaluation will become higher.

$$\begin{cases} f(x) = \dfrac{1}{V(x)} \\ V(x) = \sum_{i=1}^{n-1} d(v_i, v_{i+1}) + d(v_n, v_1) \end{cases} \tag{3}$$

If the algorithm does not meet the end conditions, then select, cross, mutation and other operations are performed to change the existing solution, that is, change the existing path.

Combination optimization with genetic algorithm is not a combination of all paths, many meaningless paths can be directly excluded, so as to save time. And our method was to use the point-to-point path planning method based on the A-star algorithm above. To begin with, we found the shortest path between any two points, and then we stored these shortest paths in the file. On this basis, we did subsequent combination optimization.

3.2 Full coverage path planning

The purpose of full coverage path planning of inspection robot is to find a path in the working space which passes through all free spaces except obstacles for mobile robot [20].

The methods of full coverage path planning are mainly divided into three categories: traditional coverage method, region decomposition method and raster map method [21]. Considering that most of the target specimens in the actual detection of transmission tower are long straight and smooth L-shaped steel members, and there is no extremely complicated obstacle form, this paper adopted the traditional covering method for full coverage path planning.

The traditional covering method mainly includes random covering method, spiral covering method and reciprocating covering method. Considering the structural form of transmission tower and the convenient movement of the inspection robot, this paper adopted a method similar to the spiral coverage method to carry out the full coverage path planning. The inspection robot started from the starting point to the outer edge gradually. When it reaches the node, it would rotate at a certain Angle and continue to traverse until the traverse was completed.

4 Path planning simulation test

Before formally carrying out the path planning in the environment of transmission tower, we firstly completed some simulation experiments in the MATLAB environment. Assuming that the robot knew the global environment information, the robot was regarded as a point and the obstacles were projected into the raster map for processing, as shown in the figure 6. The grid diagram included barrier grid and free grid. A-star algorithm was selected to carry out point-to-point path planning experiments in two-dimensional plane and three-dimensional space, and the effect diagrams were shown in figure 6 and figure 7 respectively.

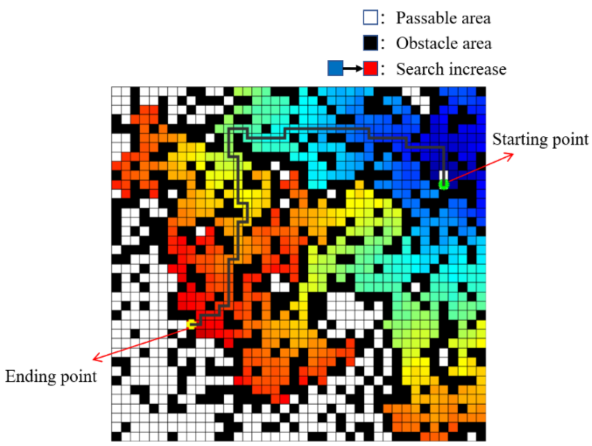


Figure 6: Experiment of two-dimensional path planning algorithm

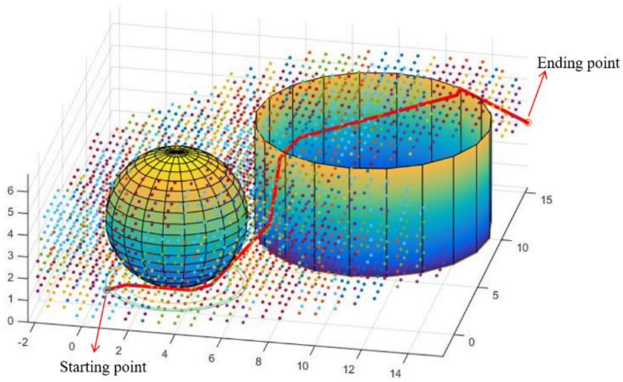


Figure 7: Experiment of 3D path planning algorithm

Then the spiral coverage method was used to plan the full coverage path with obstacles, and several obstacles were set up. In the end, the two-dimensional path planning diagram was obtained, as shown in Figure 8. However, due to the existence of obstacles, the spiral radius in the coverage would change by steps, resulting in missing coverage points, as shown in the green circle on the top left of the figure. Considering that the robot has no complex obstacles in the working environment of transmission tower, the spiral coverage method is still a simple and available method. Even in some parts of the structure, due to the large number of nodes, it is impossible to complete the full coverage path planning at one time, but it can also be traversed multiple times to achieve full coverage.

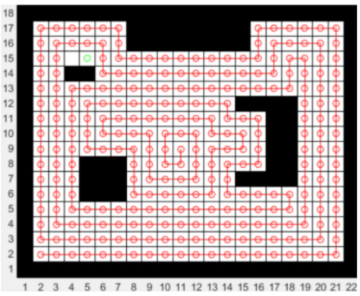


Figure 8: Spiral overlay path planning diagram

5 3D path planning of inspection robot in the background of transmission tower

As mentioned above, the path planning work of inspection robot in the background of transmission tower was based on the previous obtained 3D scanning information. Firstly, a 3D model was reconstructed from the point cloud data obtained by laser scanning. And data, mainly node coordinates, node connections and rod lengths, were obtained from the completed 3D model, and then the model was generated in MATLAB, as shown in Figure 9. The algorithm for solving the shortest path when only two points were considered was tested again. The starting point was set as one of the four points at the bottom, and the target points could be selected at will, as shown in Figure 10, which was the result of one of the planning. The red line was the running path, and the effect was very good.

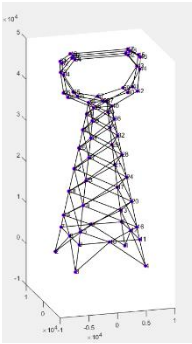


Figure 9: Model generation

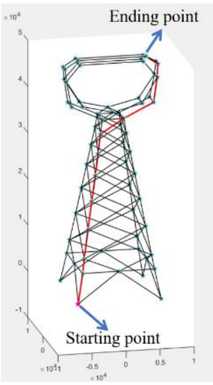


Figure 10: Algorithm test under model background

Based on the engineering background of transmission tower, the path planning of inspection robot can be converted into the basic schematic diagram in Figure 11, which is a weighted graph consisting of three sets. V is the set of measuring points. And E is the set of edges connecting two different measuring points in V. In addition, R is the set of weights of the edges. The black dots in the figure represent the measurement points needed to be detected, and there are different distances and connections between nodes.

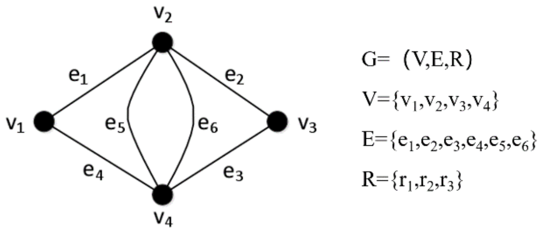


Figure 11: Basic schematic diagram

The objective function of path planning is shown in equation (4), which means that the total weighted path passed by the detection robot is the shortest.

$$f(V) = \min\left[\left(\sum_{i=1}^{n}\sum_{j=1}^{n} r_p \cdot d_{ij} \cdot x_{ij}\right) + t \cdot d_c + \sum_{k=0}^{m} w_k \cdot r_p \cdot d_k\right] \tag{4}$$

Where, r_p is the weight coefficient of the member and d_{ij} represents the length of the member from the measuring point i to j. Moreover, x_{ij} is the judgment function and t is the number of turning points. Additionally, d_c is the turning cost and w_k is the weight coefficient of the repeating member. Plus, d_k is the length of the repeating member.

There are several reasons to consider weights. The first point was because of the self-weight or inclination, the cost of the robot climbing the vertical rods and horizontal rods was not the same. So the parameter r_p of the weight of rods was set. All the rods were divided into three categories according to their different inclinations. And the corresponding weight coefficients are shown in Table 1.

Type of rod	Angle of inclination	Weight coefficient of length
Low inclination rod	<30°	1.0
Medium inclination rod	30°-60°	1.1
High inclination rod	>60°	1.2

Table 1: MBS model eigenvalues.

After a reasonable threshold being set, the category of the rod could be automatically identified in MATLAB and the length weight could be assigned, as shown in Figure 12.

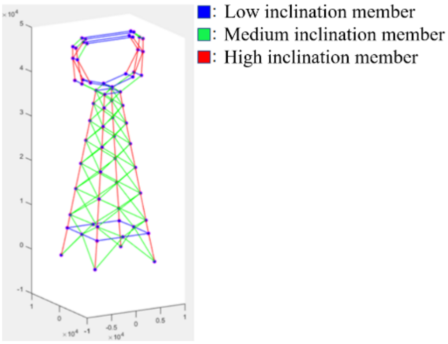


Figure 12: Automatic identification and classification of rod

The second reason was that when the robot passed through the node, if there was an attitude change such as changing from climbing the vertical rod to climbing the horizontal rod, it needed extra cost. The overhead brought by this attitude change would also be converted into the expression of distance. In this paper, we took a transition cost dc as 500mm after referring to the moving speed of the robot in the actual project such as pipeline inspection robot.

The third reason was that it was inevitable that some rods needed to be crawled repeatedly. The first crawl meant that the inspection robot was carrying equipment for detection, and the speed was slow. While the second crawl did not need detection, and it was just passing by, and the speed was faster. So the length weight value should be smaller than the first crawl. Therefore, we set an additional length weight parameter w_k for the repeated path, and we set w_k to 0.5.

In addition, another constraint was set when detecting the specified multipoint path planning of the robot, as shown in equation (5).

$$s.t.\begin{cases} \sum_{i=1}^{n} x_{ij} = 1, i \in V \\ \sum_{j=1}^{n} x_{ij} = 1, j \in V \\ \sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij} \le |S| - 1, \forall S \subset V, 2 \le |S| \le n-1 \\ x_{ij} = \begin{cases} 1, (i, j) \in L \\ 0, (i, j) \notin L \end{cases} \end{cases} \tag{5}$$

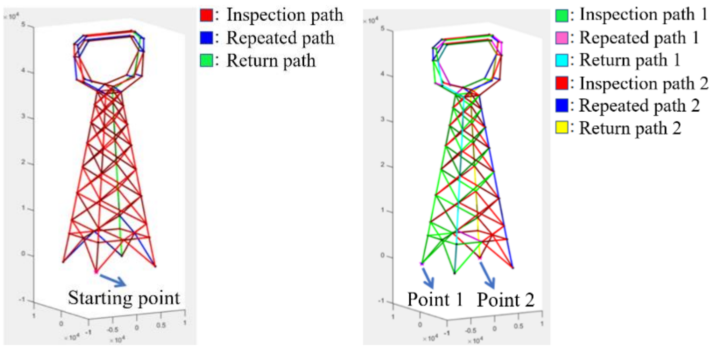
According to "Standard for inspection and appraisal of high-rise and complicated steel structures (GB51008-2016) " [22], the steel structure inspection process includes all kinds of inspection items and sampling inspection. When the inspection robot carries the equipment to carry out the inspection work, it is necessary to carry out the full coverage path planning and the designated point path planning respectively.

For all kinds of sampling tests mentioned above, the locations of target nodes and target components should be reasonably dispersed to cover all positions of the structure as comprehensively as possible, and components should be divided into different inspection batches according to different types. According to "Technical standard for in-site testing of steel structure (GB/T 50621-2010) " [23], the sampling test quantity of each test batch was reasonably selected, as shown in Table 2.

Type of rod	Item category	Detection quantity
The main material of tower body	Important item	8
The diagonal material of tower body	Important item	8
The material of tower head	General item	8

Table 2: Sampling test quantity of each test batch

Then the full coverage path planning and the path planning of the specified points for inspection robot were carried out. The effect diagrams are as follows. The situation corresponding to Figure 13 was full detection, and the situation corresponding to Figure 14 was sampling detection.



(a) One robot (b) Two robots

Figure 13: Full coverage path planning of inspection robot

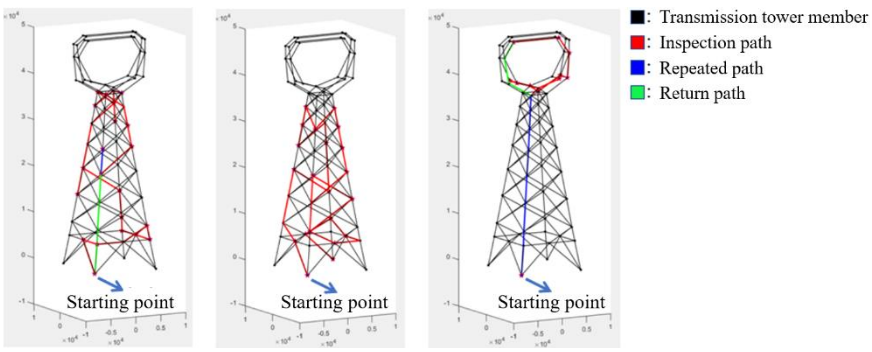


Figure 14: specified multipoint path planning of inspection robot

Because of the structural form of the transmission tower, some detecting paths may need to be repeated. For example, if we want to traverse the main material at the bottom, there will be repeated paths. Finally, the total length of the path, the number of repeated lines and the repetition rate were counted to calculate the efficiency.

6 Conclusions

In this paper, the structural information of a steel transmission tower in service was obtained by using 3D laser scanning and other new surveying and mapping technologies. On this basis, relevant detection and evaluation such as the overall inclination measurement of the structure were carried out, and a 3D model of the transmission tower was established according to the obtained data such as node coordinates, node connections and rod lengths. And the path planning of the inspection robot was carried out. Based on the simulation test, the effect of 3D path planning of inspection robot under the background of transmission tower was discussed. The following conclusions and prospects can be drawn:

(1) After integrating multi-source information, that is, when the transmission tower environment information is known, it is feasible to carry out the path planning of the detection robot, whether it is point-to-point path planning or full coverage path planning.

(2) Path planning between two points based on A-star algorithm, designated multipoint path planning based on genetic algorithm and full coverage path planning based on spiral coverage method had good application results in three-dimensional space path planning under the background of transmission towers.

(3) In this paper, when two robots participated in the full coverage path planning of the transmission tower at the same time, the results showed that the overall efficiency was not significantly improved, indicating that the algorithms or ideas of path planning need to be further improved in the joint work of multiple robots, that is, the cooperative control of multiple agents.

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