

Research on the route of electric patrol car based on spiral motion model

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Abstract. The rapid growth of photovoltaic (PV) energy has made heliostat fields essential in industrial aspects. They served as key devices for collecting and focusing solar power. How to ensure the inspecting equipment of the heliostat works efficiently in their worksite, however, has become a challenging task since the enlargement of size and complexity of our heliostat. In this study, a path-planning method based on equidistant solenoids was delivered, enabling the kart to inspect more efficiently and reducing the risk of impact. This paper improves inspection efficiency by planning the shortest route and reducing turning times, by constructing the Archimedean Spiral Motion Model and optimizing it using a binary method. According to our research, the kart we applied to this method can run smoothly, in other words, at constant speed. This paper has cut 30% of inspection time and reduced the impact risk with the heliostat. Our algorithm has effectively alerted over 90% of the underlying impact situation, which massively increased the safety and stability of the system. The research has supported a reliable technical basis in intelligent inspection in the PV energy field.

Keywords: Equidistant Spiral, Binary Method, Optimization Algorithm, Path Optimization, Shortest Path Optimization Algorithm.

1. Introduction

The global photovoltaic (PV) energy industry is experiencing rapid growth, and as one of the largest PV power generation markets in the world, the expansion of China's market scale is crucial to the global energy transition [1]. Building a new energy power system is an important measure to achieve the "dual carbon" goals. As the main facility for PV power generation, tower-type solar thermoelectric power generation utilizes low-carbon and environmentally friendly heliostat technology to collect solar energy [2]. The heliostat field, composed of a large number of heliostats, is a key device for efficient solar energy collection and focusing. However, the wide distribution, numerous quantity, and large size of heliostat fields make traditional manual inspections labor-intensive and inefficient. With advancements in current technology, the adoption of inspection robots can more effectively achieve all-weather, omnidirectional, and fully autonomous intelligent inspections, with more accurate data detection than manual inspections. To ensure the safe operation of the inspection cart, advanced path planning algorithms are needed to optimize routes and reduce inspection time and energy consumption [3]. Since inspections of circular heliostat fields require lane changes and turns, which inevitably lead to deceleration and reduced efficiency, as well as increased risks of collisions during turns, this study proposes an inspection trajectory that conforms to the circular arrangement of heliostat mirrors in the field, reducing the issues of turns and deceleration, and allowing inspections to be conducted at a nearly uniform speed, thereby indirectly increasing the productivity of the heliostat field.

This study proposes a path planning method for inspection carts based on a spiral motion model. Starting with raw data, a spiral motion model is first constructed as the basic model for the inspection route. This model aims to meet the need for comprehensive inspection of the target area by simulating

the vehicle's movement path. Furthermore, an algorithm specifically designed to monitor whether collisions occur between the vehicle and the bases is introduced. By setting up a simulated scenario—a circle with a diameter of 9m, where the circle represents the centers of the bases of a ring of heliostats—this example demonstrates in detail that the algorithm can detect the vehicle's movement status and the relative position of the bases in real-time, judge and issue early warnings for potential collision risks, thereby enhancing the system's safety and stability. On this basis, this paper further explores the feasibility of the algorithm and its potential for application in actual heliostat fields.

2. Construction and Analysis of the Spiral Motion Model

The inspiration and data for this paper come from <https://www.mcm.edu.cn/> and Bench dragon show 错误!未找到引用源。 , are planned to be scaled by an experiment in the laboratory. In the form of reduction, the heliostats model is built, and its size is specified as: mirror length is 1.65m, the width is 1.2m, the central fulcrum is 1m above the ground and the base diameter is 70cm, say the car is 30cm long and 220cm wide.

The distance between the center of gravity of the front and rear wheels is 165cm (the middle point of the front and rear wheels is used as the center of gravity).

It is set up so that the spiral trajectory of the car does not need to turn around but only needs to reverse along the circular trajectory.

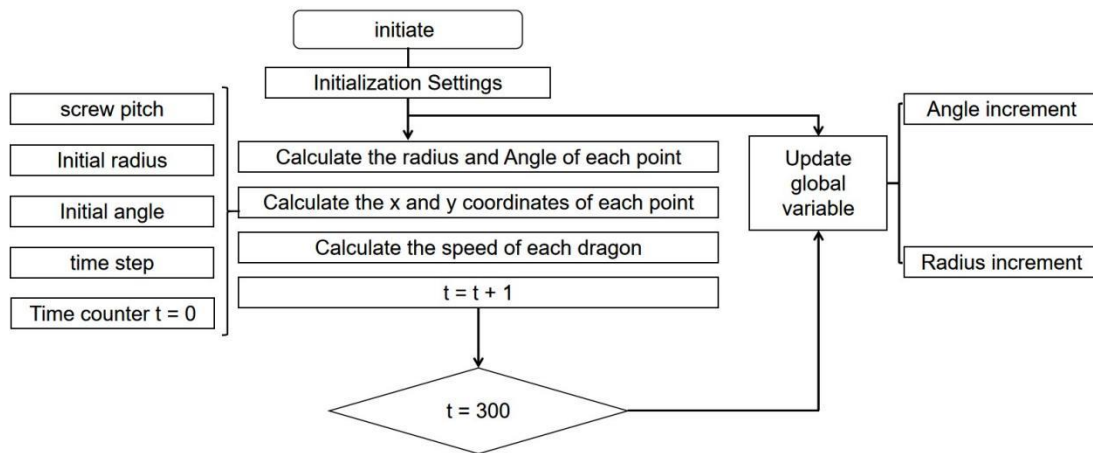


Figure 1. Model flow chart.

The specific ideas are shown in figure 1.

First, based on the conversion relationship between Cartesian and polar coordinate systems, a model of the inspection vehicle's movement path using the polar coordinate equation of an equidistant spiral is established. Then, according to the spiral parameter equation, rigid body motion equation, velocity, and acceleration formulas, the relationships between velocity, radial distance, and angular displacement of the midpoints of the front and rear axles at each moment with respect to time are derived, thus determining the kinematic model of the spiral motion of the line inspection vehicle.

In this section, the vehicle travels inward along a clockwise equidistant spiral with a pitch of 55 cm. To better describe its travel path and facilitate subsequent calculations, a polar coordinate system is established for this spiral. Referring to the literature [5], the polar coordinate equation can be expressed as:

$$\begin{cases} x_i = \rho_i \cos \theta_i \\ y_i = \rho_i \sin \theta_i \end{cases} \quad (1)$$

The helix formula can be expressed as:

$$r = a + b\theta \quad (2)$$

Which represents the position of the first handle in the Cartesian coordinate formula, because it is on the helix, so:

$$\rho_i = b\theta_i \quad (3)$$

Given that the pitch is 0.55m, the spiral parameters in formula (3) can be expressed as:

$$b = \frac{p}{2\Pi} = \frac{11}{40\Pi} \quad (4)$$

In order to simplify the calculation, the action track of the car patrol line is divided into 223 steps, the walking track of the patrol car formed by 223 line segments is 224 points in total, and the center of the front frame of the patrol car is specified as the 0 point. It can be seen that the distance between the first point and the +1 point has the following relation:

$$d_{i-i+1} = \frac{220-27.5*2}{100} \quad i = 0,1,2,...,223 \quad (5)$$

Next, the relationship between distance, speed, and time is introduced, and the coordinates are connected with time.

When $t=0$, the car is in its initial position. If the starting position of the trolley is known to be in the 16th circle of the spiral, so that $\theta_0 = 16*2\Pi$, then the starting coordinate is: $(b*32\Pi, 32\Pi)$

The velocity integral in 0-t time is as follows:

$$\int_0^t v dt = b \int_{32\Pi}^{\theta} \sqrt{1+\theta^2} d\theta \quad (6)$$

The formula is derived as follows:

$$t = \frac{0.55}{2\Pi} \left(\frac{\theta}{2} \sqrt{1+\theta^2} + \frac{1}{2} \ln|\theta + \sqrt{1+\theta^2}| - 16\Pi \sqrt{1+(32\Pi)^2} - \frac{1}{2} \ln|32\Pi + \sqrt{1+(32\Pi)^2}| \right) \quad (7)$$

Therefore, the relationship with θ and t is obtained from the above text. According to the formula $\rho = b\theta$, ρ can be obtained, thereby determining the polar coordinate positions of the points (ρ, θ) before and after the inspection vehicle.

After the relationship between time and coordinates is obtained, the polar coordinate system and Cartesian coordinate system are converted. After calculation, the starting point coordinates (x_0, y_0) can be easily obtained $(8.8, 0)$.

The distance between two points is calculated according to the formula:

$$(x_i, y_i) = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \quad (8)$$

Substitute the corresponding helix formula and simplify it to get:

$$(x_i, y_i) = \sqrt{(b\theta_i \cos\theta_i - x_{i-1})^2 + (b\theta_i \sin\theta_i - y_{i-1})^2} = d_{i-1,i} \quad (9)$$

By combining this formula with the value obtained from formula (2) and deducing the value θ_i , then the ρ_i can be deduced, the coordinates are finally calculated the coordinate (x_i, y_i) . After repeated iterative calculation, the rough inspection trajectory is obtained, and then the specific solving process is introduced

According to the above model, the target problem is solved. The solution process is shown in Figure 2:

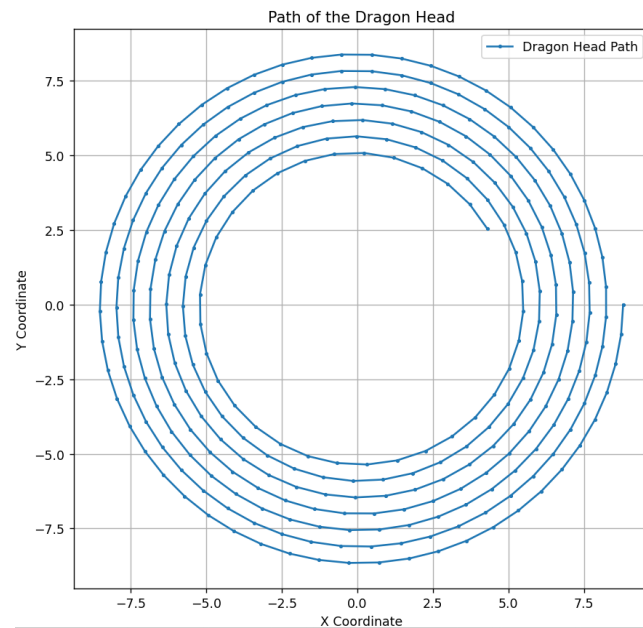


Figure 2. Route of a patrol car ($t=0$ time backward).

From Figure 2, it can be seen that the traveling route of the inspection car conforms to the arrangement requirements of the simulated mirror field. On this basis, in order to reflect whether the position relationship of each node at the initial moment is correct, whether the "faucet car length" is distinguished from the "other length". The position and trajectory of 224 handles at the initial moment are recorded in Figure 2, as shown in Figure 3.

Figure 3 shows the initial position and trajectory of the helix, with special marks for the starting point.

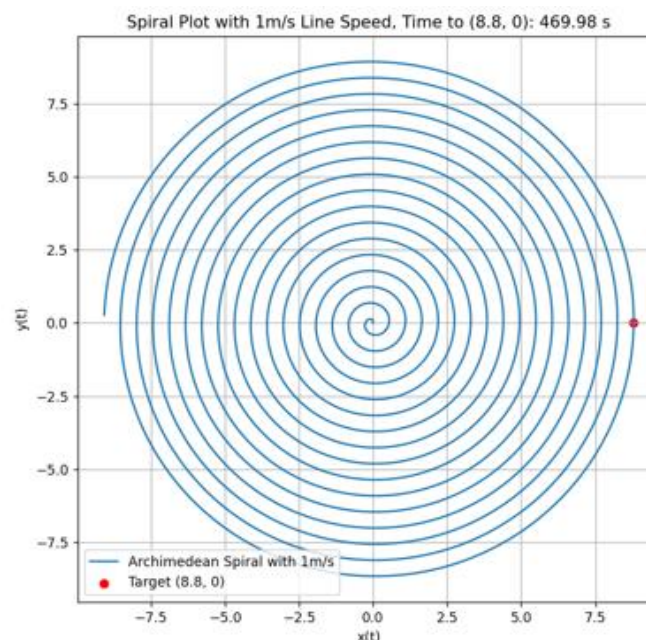


Figure 3. Initial position and trajectory of the helix.

3. Collision Prediction for Power Inspection Vehicles Traveling on a Spiral Path

Firstly, by synthesizing the research of multiple articles [6-10], this study establishes an optimization model.

As shown in Figure 4, this study assumes a circle with a diameter of 9m and a helioscope base on the circle. According to the data source, the pitch of the traveling helix of the car is 0.55m.

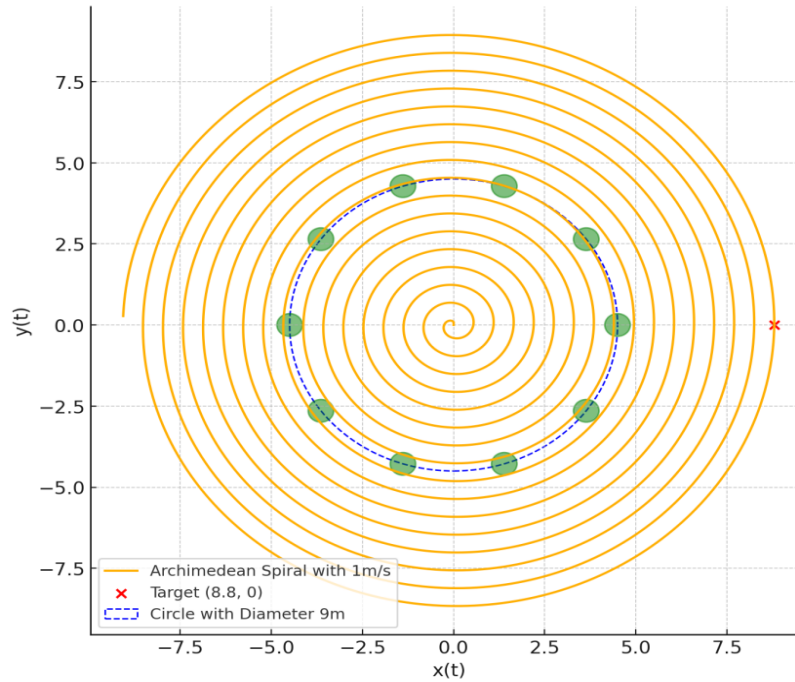


Figure 4. Schematic Diagram of Collision Model.

The image displays a simulation of a path system based on an Archimedean spiral, where the orange lines represent the travel path of a vehicle. These spirals ensure uniform coverage of the entire area. The green circles denote the bases of heliostats, which remain stationary. The blue dashed circle has a diameter of 9 meters, indicating the operational range or specific measurement boundary of the system. The red "X" mark shows the target location, with coordinates (8.8, 0). The pitch p of the spiral path followed by the vehicle is 0.55 m

Based on the polar Angle obtained above and the relationship between the two, an algorithm is introduced to detect whether the collision occurs between the patrol car and the helio-fixed base and record the collision time.

In order to more intuitively express the relationship between position coordinates (x, y) , polar diameter, ρ and polar Angle θ with respect to time t , and consider the actual situation of clockwise steering wheel entry, the parametric equation of spiral line is reorganized:

$$\begin{cases} x_i(t) = \rho(t) * \cos(-\theta(t)) \\ y_i(t) = \rho(t) * \sin(-\theta(t)) \end{cases} \quad (10)$$

Where the radius and the Angle change over time. Specific changes are as follows:

$$-\rho(t) = \rho_0 - p * t \quad (11)$$

$$-\theta(t) = \frac{t}{p} \quad (12)$$

In addition, in order to fine-tune and improve performance, and to outflow the error space, this study introduces a crucial parameter that aims to quantify the degree of deviation or the size of the gap between the inside line of the trolley and the preset base, called the "deviation distance".

$$\begin{cases} u = \dot{y} - y_i \\ u \leq 0.001 \end{cases} \quad (13)$$

In this study, the threshold of "deviation distance" was set at 0.001 m, and once the gap between the predicted value and the measured value reached this level, the first collision node was considered to be imminent. After adjustment, test again until the next collision point comes, if there is no collision point, then the path is safe.

This is the completion of the model establishment, and the next step is to solve the model.

The premise that the inspection vehicle can continue to travel clockwise along the isometric spiral is that it does not collide with any heliostat during its journey. For this reason, the central axis of the vehicle and the measured line segment of the vehicle near the spiral need to be expressed through mathematical analytic expression. Obviously, there is a parallel geometric relationship between the two line segments, which can be obtained by translation of one of the line segments. The specific relationship between the two line segments is shown in Figure 5:

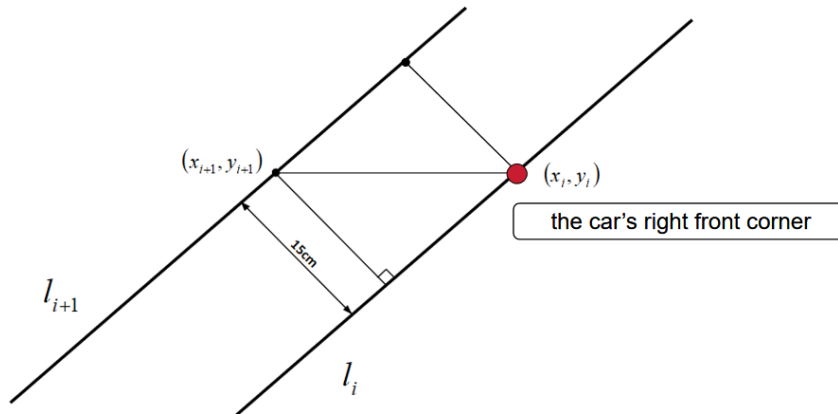


Figure 5. Geometric diagram.

Then the general linear equation of the line where the two line segments are located can be expressed as:

$$l_i : y_i = kx_i + c_i \quad (14)$$

$$l_{i+1} : y_{i+1} = kx_{i+1} + c_{i+1} \quad (15)$$

By cross-solving two points--- (x_i, y_i) and (x_{i+1}, y_{i+1}) , formula (16) can be derived:

$$y_i - y_{i+1} = k(x_i - x_{i+1}) + c_i - c_{i+1} \quad (16)$$

Since the y values of the two points are the same, there are:

$$c_{i+1} = k(x_i - x_{i+1}) + c_i \quad (17)$$

The starting point coordinates (x_0, y_0) of the known power inspection car are, and the coordinates (x_i, y_i) of the i node car are obtained according to the above. The predicted intercept c_{i+1} can be derived from the following formula:

Because the x coordinates have the following characteristics:

$$x_i - x_{i+1} = \frac{0.15}{\cos\left(\frac{\pi}{2} - \theta_i\right)} \quad (18)$$

$$x_i - x_{i+1} = \frac{0.15}{\sin \theta_i} \quad (19)$$

$$c_{i+1} = k \times \frac{0.15}{\sin \theta_i} + c_i \quad (20)$$

The inside line of the car predicted for the $i+1$ node is:

$$\dot{y} = k \dot{x} + c_{i+1} \quad (21)$$

$\dot{y}$ Can be obtained from the above formula, and then continue to substitute the calculation of the deviation value u can be obtained:

$$u = \dot{y} - y_0 \quad (22)$$

Through programming methods and iterative calculation, it can be determined whether the power inspection car will collide with the heliostat base, and get the collision time t_p . According to the t_p value, the coordinate data (t and θ) of the collision point can be known, and then the data such as the pitch of the spiral can be modified to optimize the path to conform to the base arrangement of the heliostatic field.

Certainly, the implementation of the collision avoidance algorithm for the small vehicle also plays a crucial role through the integration of sensors and cameras. After undergoing Kalman filtering, the sensors can accurately and real-time monitor the distance between the small vehicle and surrounding obstacles, while cameras based on deep learning algorithms provide more detailed environmental information through image recognition technology. This diversified data acquisition method not only enhances the accuracy of environmental perception but also improves the system's response speed. By setting a safety distance threshold, the algorithm can effectively assess the distance between the small vehicle and obstacles; if the distance falls below the established safety threshold, the algorithm promptly issues an alert and adjusts the vehicle's trajectory, employing actions such as slowing down, steering, or stopping to avoid collisions. Additionally, by integrating machine learning algorithms, the system can continually learn and optimize avoidance strategies, thereby enhancing flexibility and adaptability in various environments.

4. Conclusions

This paper presents a model combining the helical line model with the finite difference method, aiming to optimize the inspection path of equipment in the photovoltaic field. Through this model, the kinematic characteristics of objects, such as speed, acceleration, and trajectory changes, can be precisely simulated and analyzed, while their stability and response speed are evaluated. This method not only provides a clear mathematical definition and parameter equation, making it easy for numerical calculation and simulation, but also effectively avoids collision problems in actual operation. The algorithm framework has shown certain application potential and feasibility in the photovoltaic-related field, especially in the inspection path optimization of heliostat fields, and is expected to improve equipment performance and efficiency.

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