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RESEARCH ARTICLE

An Automatic Route Planning Method for Digital Transmission Lines Based on Remote Sensing Spatial Model of Ground Obstacles and Ant Colony Algorithm

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Abstract
Transmission lines often need to cross various complex geographical environments, such as mountainous areas, rivers, forests, etc., where the terrain and landforms are complex and varied. In order to address the challenges faced by transmission line path planning and solve the problems of traditional planning methods relying on manual experience, outdated maps, and existing research methods such as the inability to completely avoid obstacles, high planning costs, and susceptibility to dimensional disasters, a digital transmission line automatic path planning method based on ground obstacle remote sensing spatial model and ant colony algorithm is proposed. Using unmanned aerial vehicles equipped with remote sensing sensors to collect ground data, extracting key features through preprocessing, constructing a ground obstacle spatial model, and estimating construction costs. On this basis, combined with an optimized ant colony algorithm, automatic planning of transmission line paths based on cost–benefit analysis was achieved, and a detailed planning cost map was drawn. Experiments have shown that this method can effectively avoid impassable areas in transmission lines, remove unnecessary corners in feasible areas, and plan construction with low difficulty and cost. The planning accuracy is higher than 98%, and the performance is good.

Keywords Ground obstacle · Spatial model · Ant colony algorithm · Transmission line · Raster matrix · Path planning

Introduction

In power grid construction projects, a reasonable transmission line path is the foundation for the construction of a high-quality power grid (Xuegong & Yaqing, 2020). Traditional path planning mainly relies on the accumulated experience of the staff, which has the disadvantages of high labor intensity and long planning time, and the map referenced by the staff also has serious lag. In this case, the transmission line path formulated by the traditional method often fails to achieve the ideal effect (Lan et al., 2020; Maomao & Bing, 2022; Shihua et al., 2021). In order to improve the speed and rationality of path planning, it is very meaningful to find a suitable modern technology to plan the transmission line path.

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In recent years, many scholars at home and abroad have done a lot of research on transmission line path planning, and achieved certain results. For example, Song Tao and others have studied a digital transmission line path planning method based on hierarchical reinforcement learning. This method establishes a three-dimensional digital cloud platform for transmission lines, resamples terrain data with different scales, reconstructs the original terrain into a coarse-grained and fine-grained two-layer grid map, and combines hierarchical reinforcement learning based on the MAXQ algorithm for path planning. However, this method cannot completely avoid ground obstacles (Tao et al., 2022). Xie Jinghai and others have studied the key technology of transmission line path planning based on the improved ant colony algorithm. This research takes the ant colony algorithm as the core, uses Remote sensing technology (RS) to obtain the geographical information of remote sensing images in the planning area, quantifies and integrates the complex geographical information, and realizes the automatic planning of digital transmission line paths. However, this method has the problem of high cost of path planning (Xie Jinghai et al., 2020). Sheng Jinma and others built the transmission line path optimization function with the help of a geographic information system, and introduced the two-way strategy into the one-way dynamic programming algorithm to solve the objective function, and then completed the transmission line planning (Jinma et al., 2022). However, this method needs a lot of memory space, and it is prone to overestimation, which affects the effect of path planning. Xie Jinghai and others use the cloud platform combined with GIS technology to digitally simulate the geographic information of the transmission line planning area, and build a cost evaluation model, which is equivalent to a grid matrix. On this basis, Q-learning algorithm is used to plan the transmission line path (Jinghai et al., 2021); Although the above method has played a certain role in planning the transmission line path, it is prone to the problem of dimension disaster when dealing with large-scale data, and the path planning is not ideal. Gu Yuhai and others proposed a global path planning algorithm based on the A * algorithm to address the problems of large search range, low efficiency, and multiple turning points in path planning on high-resolution remote sensing images Introducing cosine function into the heuristic function of the original A * algorithm reduces the search process of redundant nodes, narrows down the range of algorithm search nodes, and improves the efficiency of algorithm operation; Design a turning point optimization plan to reduce unnecessary turning points in the planned path and improve the smoothness of the path planning results (Yuhai et al., 2024); Cao Yi and others proposed a path coverage method for unmanned boats based on ocean remote sensing images Firstly, in order to establish an accurate map model, a rotation target detection algorithm based on improved YOLO V3 is proposed. On the basis of YOLO V3, the axial, length, width, and coordinate information of obstacles are refined to improve the recall rate of obstacle detection in complex scenes without increasing computational complexity Then, in order to obtain an efficient coverage path, a path coverage algorithm based on rotating beam and greedy algorithm was proposed This algorithm divides the complete path into straight path and turning path, and optimizes the coverage path based on length and obstacle avoidance objectives, respectively (Yi et al., 2023).

Remote sensing technology is based on the principle of electromagnetic waves and uses high-altitude sensing equipment to detect and identify remote targets on the ground (Jinju et al., 2021). Ant Colony Optimization (ACO), as a heuristic optimization algorithm, has shown excellent performance in solving complex optimization problems due to its advantages such as positive feedback mechanism, distributed computing, and strong robustness. Ant colony algorithm simulates the foraging behavior of ants in nature, by releasing and perceiving pheromones along the path to find the shortest path. In the problem of transmission line path planning, ground obstacles can be regarded as obstacles in ant colony algorithm, and the path of transmission lines can be regarded as the walking path of ants (Zuohua et al., 2022). Ant colony algorithm is used to search for the optimal or suboptimal transmission line path. The method proposed in this article combines the advantages of remote sensing technology and ant colony algorithm. The ground obstacle remote sensing spatial model constructed using unmanned aerial vehicle data collection can accurately extract ground features and provide accurate geographic information basis for path planning. Compared with some traditional methods that rely on experience or a single data source, it is more scientific. At the same time, the improved ant colony algorithm effectively improves search efficiency and planning accuracy through variable step size crossing strategy and angle processing strategy, demonstrating better adaptability when facing complex terrain and large-scale data. The main structure of the article is as follows:

(1) Perform histogram equalization on the collected ground remote sensing image data, enhance the contrast of the ground remote sensing image by stretching the pixel intensity distribution range, extract ground features, and introduce the decision function of the support vector machine to construct a ground obstacle remote sensing spatial model.
(2) Based on the established digital remote sensing spatial model of the transmission line planning area, evaluate the construction costs of different types of areas, divide the ground similar to the power grid into different levels according to the cost level, equivalent the transmission line path to a weighted matrix, and plan and design the transmission line path.
(3) In the process of using ant colony algorithm for transmission line path search, the cross strategy is introduced to improve the ant colony algorithm, and the automatic planning of digital transmission line paths based on ground obstacle remote sensing spatial model and ant colony algorithm is completed.

In summary, this article utilizes remote sensing technology to collect ground data. Through a UAV equipped with remote sensing sensors, it can acquire information about ground obstacles with high precision. Then, a remote sensing spatial model is established based on these data, which lays a solid and accurate foundation for the path planning of transmission lines. In addition, an intelligent optimization algorithm called ant colony algorithm is introduced. The algorithm can automatically search and optimize the path, thus significantly improving the accuracy and efficiency of the planning process.

Automatic Transmission Line Path Planning

Establishment of Remote Sensing Spatial Model of Ground Obstacles

Ground obstacles refer to natural or man-made objects located within the planned area that may have adverse effects on the construction or operation of transmission lines. In the process of transmission line path planning, the main factors to be considered are the safety of power grid operation, the economy of construction cost, the convenience of construction and the integrity of natural ecological environment along the line (Haodong et al., 2022; Lanfeng et al., 2020). In order to design the best transmission line path that meets the standard, it is necessary to construct the remote sensing spatial model of ground obstacles in the planning area first. This model can intuitively display the terrain, vegetation distribution, building location and other information within the planning area, providing an important basis for subsequent path planning.

In RS technology, multi-band scanning (TM) image is widely used, which has high resolution and small space ratio, and is more suitable as a carrier for collecting geographic information of transmission lines. When TM images are collected, it can be realized by unmanned aerial vehicles carrying remote sensors. This method has the advantages of high resolution, low cost, low risk, fast aging and convenient and flexible application. Set the ground data collected by UAV (Unmanned Aerial Vehicle) as $R(x, y)$. Considering the problems of noise and poor visual effect in the initially collected data of ground information, in order to avoid this problem from affecting the accuracy of building the spatial model of ground obstacles by remote sensing, thus affecting the accuracy of automatic planning of digital transmission line paths, the initially collected ground remote sensing data are preprocessed. Through preprocessing, the visual effect of the image is improved and the characteristics of ground obstacles are highlighted, so as to remove all kinds of errors and distortions formed in the process of collecting remote sensing data and better reflect the ground information of transmission line path planning, so as to facilitate the subsequent feature extraction and model construction.

Histogram equalization can significantly improve the contrast of an image, making the details in the image clearer, which is very beneficial for subsequent feature extraction and model construction. In order to achieve the goal of stretching the pixel intensity distribution range, significantly improving image contrast and making image details clearer, this is very beneficial for extracting features of ground obstacles from the image and constructing related models in the future. It can reduce misjudgments and errors caused by poor image quality and provide a better data basis for the entire transmission line path planning. The formula is as follows (Haodong et al., 2024):

$$A(x, y) = \frac{n \sum_{x=0}^{n} \sum_{y=0}^{m} R(x, y)}{m} \tag{1}$$

where $R(x, y)$ represents the collected initial ground remote sensing image data, n represents the number of pixels with the pixel value of x, and m represents the number of pixels with the pixel value of y.

In order to effectively improve the problem of insufficient smoothness in images, reduce image noise, and thereby improve the signal-to-noise ratio of images, further enhance the accuracy of subsequent feature extraction and model construction, and ensure the reliability of the entire path planning process. The formula is (Jing & Qingyan, 2024):

$$A'(x, y) = \sum_{x=0}^{n} \sum_{y=0}^{m} R(x + \Delta x, y + \Delta y) * B(\Delta x, \Delta y) \tag{2}$$

where Δx, Δy represent the pixel variation, and $B(\cdot)$ represents the median filter function of the filter.

After preprocessing the ground remote sensing image data collected by UAV, the ground features are extracted based on the preprocessed data. Ground feature extraction is to extract useful information from the preprocessed image, so as to build the subsequent remote sensing spatial model of ground obstacles. These features include spectral features, shape features and texture features. In transmission line path planning, spectral features can be used to identify obstacles that may affect line construction, such as buildings, roads, etc. These obstacles often exhibit significant differences in spectral characteristics compared to their surrounding environment. Shape features help accurately determine the position and range of obstacles. In transmission line path planning, obstacle areas that need to be avoided can be accurately identified through shape features. Texture features can provide richer details of land features. In transmission line path planning, texture features can further distinguish different types of obstacles (such as vegetation density, building materials, etc.), thereby more accurately evaluating their impact on path construction.

The extraction methods for spectral features, shape features, and texture features are as follows:

The spectral feature is to directly extract the pixel index of the image, and the calculation NDVI formula is (Gaoyang et al., 2024):

$$C_1 = \frac{c(A'(x, y)) - c'(A'(x, y))}{c(A'(x, y)) + c'(A'(x, y))} \tag{3}$$

In the formula, $c(A'(x, y))$ represents the reflectivity in the near infrared band and $c'(A'(x, y))$ represents the reflectivity in the red band.

After determining the spectral characteristics, the shape characteristics of the ground remote sensing image are extracted, and the shape parameters of the segmented obstacle object can be calculated. The characteristic formula is (Jianhua et al., 2023):

$$C_2 = \sum_{x=0}^{n} \sum_{y=0}^{m} d(A'(x, y)) \tag{4}$$

where $d(A'(x, y))$ represents the area of each pixel in the object.

Image texture plays an important role in the construction of spatial model, and also has a direct impact on the subsequent automatic planning of digital transmission lines. Therefore, to extract the texture features of ground remote sensing images, this step uses the gray level co-occurrence matrix method to extract the texture features, and the formula is (Zhentao et al., 2022):

$$C_3 = \frac{\sum_{x=0}^{n} A'(x-e, y) \sum_{y=0}^{m} A'(x, y-e) + e'}{n * m} \tag{5}$$

where e represents the separation distance between pixel pairs, and e' represents the offset determined according to the direction and distance.

On the basis of extracting ground remote sensing image features, orthorectified images are generated through aerial triangulation and stitching for equalization and balance correction of ground remote sensing image features. The decision function of the support vector machine is introduced to construct a ground obstacle remote sensing spatial model. The calculation formula can be expressed as (Xiaoxian et al., 2021):

$$\begin{gathered} F(x) = \operatorname{sign}\left(\sum_{k=1}^{K} \alpha C_k G\left(x_i, y\right) + h \right) \\ C_k \in \left\{C_1, C_2, C_3\right\} \end{gathered} \tag{6}$$

where sign(·) represents the symbolic function, α represents the Lagrangian multiplier, $G(\cdot)$ represents the RBF kernel function, and h represents the bias term, C_k represents the characteristic values of different bands or different types of characteristic vectors. Extract key features that can characterize ground characteristics and construct feature vectors. These features cover information such as topography, landforms, and different types of land cover. Clearly label which ones belong to the category of ground obstacles and which ones belong to the category of non obstacles, and use them as corresponding category labels. Integrate these feature vector data with clear category labels to form a complete training dataset. During the training phase of SVM, based on these data, the optimal hyperplane or decision boundary is continuously searched for by adjusting the Lagrange multiplier and using RBF kernel functions, so that the model can accurately distinguish between obstacles and non obstacles, achieving precise recognition of ground obstacles.

Through the preprocessing of ground remote sensing image data and the feature extraction of ground obstacles, combined with the decision function of the support vector machine, the construction of a remote sensing spatial model of ground obstacles can be realized, and the transmission line path suitable for local characteristics can be designed according to this geographical spatial model. The specific establishment process is shown in Fig. 1.

Grid Matrix Construction of Transmission Lines Based on Grid Cost Instead of Value Evaluation

Due to the intricate geographical terrain for power line construction, there are costly regions like rivers and mountains, and impassable areas requiring detours (obstacles). Therefore, costs must be evaluated for various terrain types using a digital remote sensing model of the planned area. Subsequently, a grid framework is established to plan the most efficient route for the power lines. Estimate the cost of all areas, divide the grid-like ground into different grades according to the cost level, and equivalent the transmission line path to a weighted matrix, namely grid matrix M, which is described as (Shuangxi et al., 2024):

$$M(x, y) = \begin{bmatrix} m_{11}(F(x, y))\, m_{12}(F(x, y)) \cdots m_{1i}(F(x, y)) \\ \cdots \cdots \cdots \cdots \\ m_{1j}(F(x, y))\, m_{2j}(F(x, y)) \cdots m_{ij}(F(x, y)) \end{bmatrix} \tag{7}$$

where, $M(x, y)$ represents a two-dimensional grid matrix used to represent the cost weight information of the entire planning area, m_{ij} represents the planning cost weight of the corresponding region block, i and j represent matrix indices, used to specify the specific element positions in the matrix, $F(x, y)$ represents grid region feature information. Distinguish land cover types through spectral feature analysis, and calculate the value of $F(x, y)$ based on the corresponding cost coefficients and weights of each factor. Construct a grid matrix based on the coordinates of each grid position within the planning area.

According to Formula (7), the transmission line planning cost map can be drawn, as shown in Fig. 2. This article collects cost data from authoritative economic statistics departments, engineering construction industry reports, and local actual construction projects, covering aspects such as land acquisition costs, fluctuations in construction material

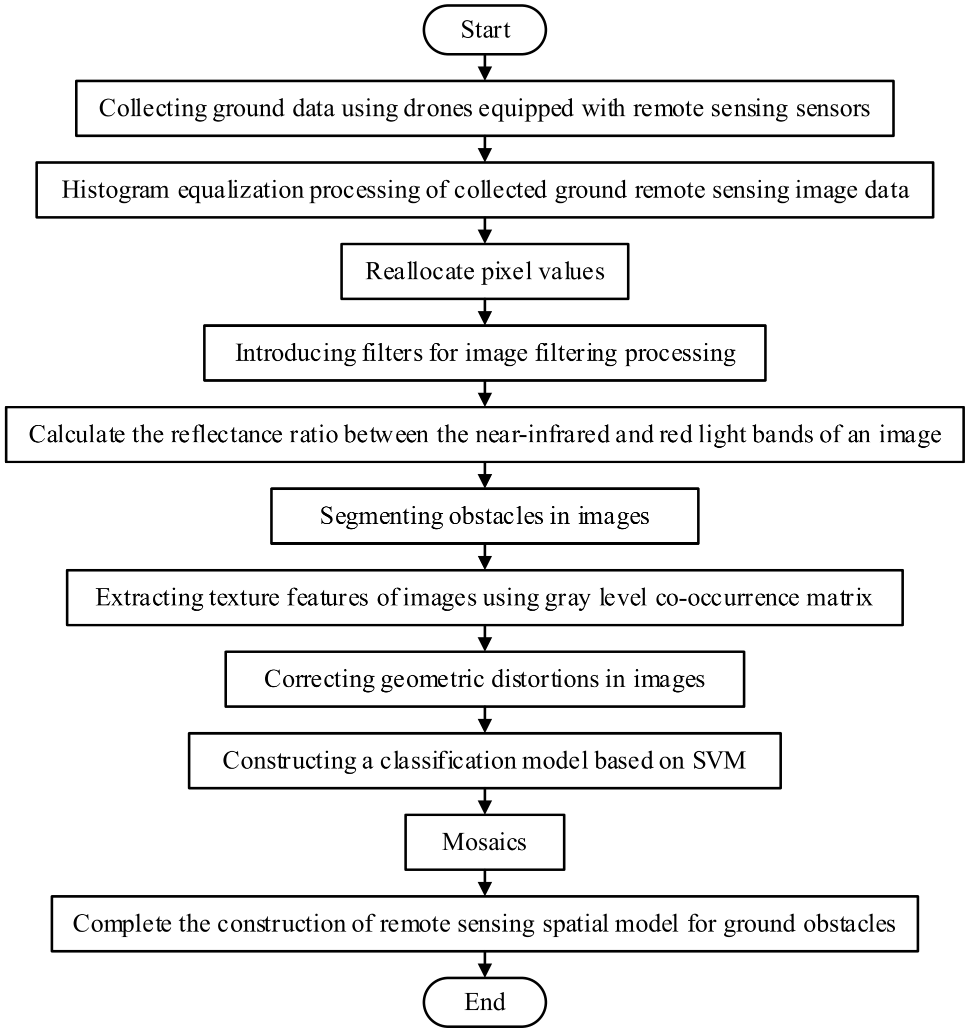


Fig. 1 Process for Establishing a Remote Sensing Spatial Model of Ground Obstacles

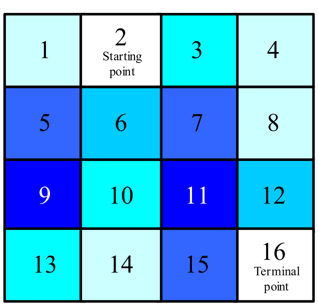


Fig. 2 Cost diagram of transmission line path planning based on grid matrix

prices, and changes in labor costs. When constructing a ground obstacle spatial model and conducting grid matrix cost assessment, use these latest data to accurately adjust the cost weights for different terrains and regions.

In Fig. 2, darker colors represent higher costs, with areas 9 and 11 being the most costly due to their deep color, suggesting impassable facilities. Based on this cost map, the path for the power line can be strategically planned and designed.

Automatic Transmission Line Path Planning Based on Improved Ant Colony Algorithm

According to the grid matrix in Sect. "Grid Matrix Construction of Transmission Lines Based on Grid Cost Instead of Value Evaluation", the improved ant colony algorithm is applied to plan the best digital transmission line.

Transmission Line Path Search Based on Traditional Ant Colony Algorithm

Ant colony algorithm (ACO) is a simulated evolutionary algorithm, and its search for the best path is usually carried out according to the following two rules: one is the moving rule, which is used to determine the moving direction of ants (Lanfeng et al., 2020); The other is the pheromone updating rule, and the ant colony moves towards the optimal solution according to the guidance of pheromones in the path.

Let i describe the location of the grid where ants will arrive next, then the probability of grid o to i can be obtained after normalization (Lei et al., 2024):

$$p_{oi}(x,y) = (c_{oi}^{\alpha}(M(x,y))\tau_{oi}^{\beta}(M(x,y))) / \sum_{i=1}^{N} c_{oi}^{\alpha}(M)\tau_{oi}^{\beta}(M(x,y)) \quad (8)$$

where, the reciprocal of the distance from o to i is described by c_{oi}. The pheromone concentration is described by τ_{oi}, the control intensity is described by α and β, and the number of optional surrounding grids is described by N.

Formula (8) can be used to get the probability that the adjacent grid is selected, and the next position can be determined by roulette. In this process, a random number $r \in [0,1]$ will be randomly formed. If $\sum_{i=1}^{n} p'_{oi} \geq r$, then i is the location where the ants will arrive next.

When the ant colony searches for a feasible digital transmission line path, it needs to update τ existing in the grid, and at the same time, introduce the volatilization coefficient σ about τ to avoid the premature problem. The pheromone update can be described as follows (Wenqian et al., 2024):

$$\tau_i'(x,y) = (1-\sigma)(\tau_i(x,y) + \Delta\tau) \quad (9)$$

where $\sigma \in (0,1)$, the pheromone concentration before updating and the added value are described by τ_i and $\Delta\tau$ respectively.

Transmission Line Path Planning Based on Improved Ant Colony Algorithm

Because the traditional ACO algorithm has a small search step size, it can't perform a leap-forward search, and it is prone to the problem of path detour, and the search efficiency is also low. Therefore, this paper introduces two strategies to improve it.

(1) Variable Step Spanning Strategy

In the traditional ACO algorithm, when ants move to the next position, they choose eight grids around them, which leads to low search efficiency when facing large-scale data, which is not conducive to the location of towers. By introducing the crossing strategy into it, the grid can be searched, which can effectively reduce the search times of digital transmission line path planning and improve the search efficiency on the premise of ensuring accuracy.

If only the fixed step size is used to search the path, it may appear that all the grids within the fixed step size are infeasible areas. To avoid this, the variable step size strategy should be introduced, that is, when all the adjacent grids are infeasible, the step size will be automatically changed until a grid is feasible.

(2) Corner handling strategy

For transmission lines, the cost of tower and foundation is a high cost part. When the tension segment of the obtained path is short and has many angles, the cost will increase accordingly. Because the grid is used to search for the best path of transmission lines, there will be redundant corners in this process. When the transmission line is to be built at A and E, the path in Fig. 3 will be formed.

As can BE seen from Fig. 3, after starting from point A and passing through point B, there are obstacles in the BE direction. In order to reach point E smoothly, we will turn at point B, and then pass through points C and D to reach point E. However, as can be seen from the figure, this line is not the optimal path, but the line $A \rightarrow D \rightarrow E$ is the optimal.

In order to find the truly feasible and optimal transmission line path, a corner treatment strategy can be introduced, that is, the slopes of line segments AB and AC composed of three continuous points A, B and C are compared. When the slopes of the two are different, then evaluate whether AC passes through the insurmountable area, and compare the costs of AC and $AB+BC$. If there is no insurmountable area on AC and its cost is less than the cost of $AB+BC$, then B is eliminated and AC is taken as the path of this section. According to the above ideas, the treatment of redundant corners can be completed.

To sum up, the automatic path planning of digital transmission lines based on the ground obstacle remote sensing spatial model and ant colony algorithm, the specific steps are as follows:

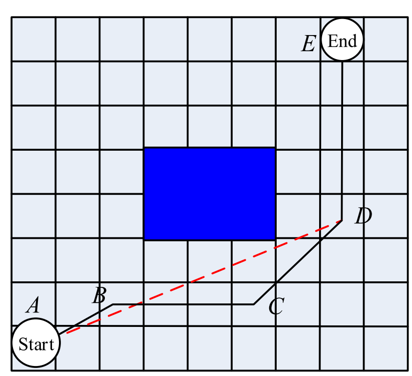


Fig. 3 Schematic diagram of transmission line path search when there are obstacles

(1) The original remote sensing images of transmission line path planning area are collected by RS technology, and the ground obstacles are extracted. On this basis, a digital remote sensing spatial model of the transmission line planning area including ground obstacles is established.
(2) Through the method of quantitative scoring, the cost of transmission line planning in each planning area in the grid is estimated, and the cost map of transmission line path planning based on grid matrix is drawn.
(3) parameter initialization. Initialize the parameters such as the size of ant colony, the number of iterations, the starting point and ending point of the path, the initial value of pheromone, control intensity and so on.
(4) Use Formula (8) to determine the grid to be reached in the next step, and so on to obtain the whole transmission line path, and estimate the line cost from the starting point to the current grid, and keep the results. The cost formula is (Li & Xi, 2023):

$$L_i = w_1 M(x,y) p_{oi}(x,y) + w_2 T_1 + w_3 T_2 + w_4 T_3 \quad (10)$$

where $w_{1,}$ $w_{2,}$ w_3 $_{\text{and}}$ w_4 represent the corresponding weights, and $T_{1,}$ T_2 $_{\text{and}}$ T_3 are the length between grids, the density of obstacles from grid to grid and the complexity of terrain fluctuation from grid to grid respectively.
(5) Using the corner processing strategy, the redundant corners in the obtained route are processed to obtain the final path result of this round, and the results are kept.
(6) Compare the obtained path planning result of this round with the saved optimal path, and replace it if it is better.
(7) judging whether the running times are reached, and if not, jumping to step (4); If it has been reached, proceed to the next step.
(8) Use Eq. (9) to update τ of the optimal planning path, obtain a new τ, and judge whether it meets the algorithm termination standard, if not, jump to Step (4); If yes, the algorithm ends, and the final path result is output to obtain the optimal planned path of the transmission line, and the formula is (Yuxin et al., 2021):represent the corresponding weights, and

$$L = \sum_{i=1}^{N} L_i \quad (11)$$

At this point, the design of digital transmission line path automatic planning method based on ground obstacle remote sensing spatial model and ant colony algorithm is completed.

Experimental Analysis

Experimental Preparation

This article takes the installation project of a power transmission line in a certain province as the experimental object, and uses a high-altitude unmanned aerial vehicle equipped with SPECIM IQ remote sensing sensor to collect remote sensing images of the planned area. The flight altitude is 100 m, the speed is 5 m per second, the forward overlap rate of the route is 80%, and the lateral overlap rate is 30%. The resolution of the collected images is 5 cm per pixel, which serves as the data basis for constructing a ground obstacle remote sensing spatial model and subsequent analysis. The altitude along the line is about 20 m to 30 m, and the whole line planning area mainly includes cultivated land, rivers, urban areas and flat land.

In order to verify the effectiveness of this method, the transmission line path is automatically planned by this method. Taking into account the characteristics of ant colony optimization algorithm and the specific requirements of transmission line path planning, it is concluded that in terms of population size, it determines the number of ants searching for the solution space simultaneously. If it is too large, the computational cost will increase dramatically, while if it is too small, it will be difficult to find the global optimal solution. After weighing 30, it is a moderate value that can balance efficiency and computational burden. The control intensity α is related to the importance of pheromones in ant path selection. Although a larger value helps to converge quickly, it is prone to premature convergence. Option 2 aims to balance the exploration of new solutions and the utilization of existing information. The control intensity β determines the weight of heuristic information, and setting it to 3 can enable ants to quickly locate better directions in the early stages of search based on this. The volatility coefficient affects the attenuation of pheromones. A value of 0.3 can retain some historical information to guide search and encourage ants to explore new paths, avoiding the algorithm from getting stuck in local optima. Based on these factors, the experimental settings in Table 1 were determined.

Table 1 Settings of main parameters of the experiment

Parameter name	Numerical value
Population size	30
Control intensity α	2
Control intensity β	3
Volatility coefficient of pheromone	0.3
Grid matrix size	50 m × 50 m

In the parameter settings of Table 1, the population size determines the number of ants searching the solution space simultaneously in the algorithm. A larger population can provide more search paths, increasing the likelihood of finding the global optimal solution, but it also increases computational costs. 30 is a relatively moderate value that can avoid excessive computational burden while maintaining search efficiency.

The alpha parameter determines the importance of pheromones in ant path selection. A larger alpha value will make ants more inclined to choose paths with higher pheromone concentration, which helps the algorithm converge quickly to a better solution, but may also lead to premature convergence. Choosing 2 as the value of α is an attempt to find a balance between exploring new solution spaces and utilizing known information.

The β parameter determines the importance of heuristic information in ant path selection. A larger β value will make ants more dependent on heuristic information to choose paths, which helps to quickly find better solutions in the early stages of the search and guide the search direction towards the global optimal solution. Therefore, the value of β is set to 3.

The volatility coefficient of pheromones determines the decay rate of pheromones over time. A smaller volatility coefficient means that pheromones are retained for a longer time, which helps ants to continuously utilize previous information, but may also lead to the algorithm getting stuck in local optima. Choosing 0.3 as the volatility coefficient can encourage ants to explore new paths while maintaining certain historical information.

In summary, the parameter settings in Table 1 are reasonable choices based on the characteristics of ant colony optimization algorithm and specific problem requirements. These parameters collectively affect the search behavior, convergence speed, and global search capability of the algorithm. By adjusting these parameters, better optimization results can be achieved in different problem scenarios.

Remote Sensing Image Preprocessing and Regional Quantification of Transmission Line Path Planning

Using high-altitude unmanned aerial vehicles equipped with SPECIM IQ remote sensors to collect and preprocess remote sensing images of the planned area, with 5 bands. Firstly, the collected ground remote sensing image data is subjected to histogram equalization, which enhances image contrast by stretching the pixel intensity distribution range, making image details clearer, reducing misjudgments and errors caused by poor image quality, and laying the foundation for subsequent feature extraction. Then, a filter is introduced to filter the image, effectively improving the signal-to-noise ratio and further enhancing the accuracy of subsequent feature extraction and model construction. On this basis, the spectral, shape, and texture features of ground obstacles are extracted. Spectral features can identify obstacles that affect line construction, shape features can determine the location and range of obstacles, texture features distinguish different types of obstacles, and then combined with the decision function of support vector machine to construct a remote sensing spatial model of ground obstacles, providing accurate geographic information basis for path search of ant colony algorithm and optimizing transmission line path planning. The resolution of the collected image is 5 cm per pixel, as shown in Fig. 4.

This resolution can clearly present the terrain, vegetation, buildings, and other ground features within the planning area, providing a more accurate data foundation for subsequent ground obstacle extraction, spatial model construction, and transmission line path planning. However, with the deepening of research and the continuous improvement of precision requirements, there is still room for further improvement.

After filtering, the noise in the image is effectively suppressed and the signal is enhanced. The possible interference factors such as spots and clutter have been significantly reduced, making the image smoother and more stable. Not only does it further enhance the visual effect of the image, but it also provides a more reliable data foundation for subsequent analysis and model construction, making the ground obstacle remote sensing spatial model constructed based on these processed images more accurate in reflecting the actual geographical environment, thereby improving the accuracy of transmission line path planning. The filtered processed image is shown in Fig. 5.

After the ground obstacles are extracted, the spatial model of digital power line planning area is constructed, and the quantitative indicators are scored. According to the

Fig. 4 Pre-processed remote sensing image

Fig. 5 Filtered image

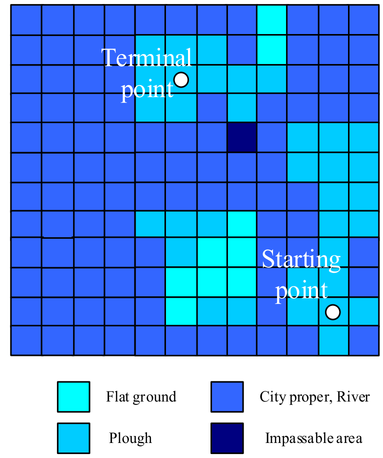


Fig. 6 schematic diagram of transmission line path planning cost

characteristics of different land cover types and their impact on transmission line construction, corresponding weights are assigned. For example, complex terrains such as rivers and mountains are given higher weights, while flat farmland is given lower weights. Then, for different land cover types within each grid cell, multiply their proportion by the corresponding weight and sum them up, then divide by the total area of the grid cell to obtain the average cost or comprehensive evaluation value of the grid, as shown in Table 2.

In order to present the outstanding effect of the proposed method compared to other possible paths more intuitively and clearly, a cost chart for transmission line path planning was drawn, as shown in Fig. 6.

As can be seen from the remote sensing image in Fig. 4, the landform of the transmission line planning area is complex, including urban areas, cultivated land, rivers, plains, etc., in which the urban areas and rivers occupy a large area. According to the quantitative indicators of the transmission line path planning are shown in Table 2, it can be seen that the erection cost of these two parts is high and should be avoided as far as possible. The population size determines the number of ants searching the solution space at the same time, if the scale is too large, although it can increase the possibility of finding the global optimal solution, but it will increase the computational burden, for example, in the paper, we chose 30 as a moderate value, which can guarantee the efficiency of the search and at the same time avoid the high computational cost; the alpha parameter controls the importance of the pheromones in the ants' path selection, and a larger value makes the ants tend to select the paths of high pheromone concentration, which is good for fast convergence but may lead to premature convergence. The alpha parameter controls the importance of pheromones in the ants' path selection, a larger value makes the ants more inclined to choose the path with a higher concentration of pheromones, which is conducive to fast convergence but may lead to premature convergence, and the choice of 2 is to seek a balance between exploring new solutions and utilizing the known information. A value of 0.3 encourages the ants to explore new paths while retaining some historical information. These parameters interact with each other to affect the algorithm's search behavior, convergence speed, and global search capability. In addition, according to the schematic diagram of transmission line path planning cost in Fig. 6, it can be seen that there is an impassable area (the darkest color) between the starting point and the ending point, so it should be avoided when planning the transmission line path.

Table 2 Regional Quantitative Indicators of Transmission Line Path Planning

Parameter name	Cost estimation weight
Flat ground	0.5
Plough	0.7
Hilly area	1.0
Hills	0.6
Desert	0.4
City proper	1.0
River	1.0
Glaciation	0.5
Impassable area	2.0

Results of Automatic Path Planning of Digital Transmission Lines

The planning results obtained by this method are shown in Fig. 7.

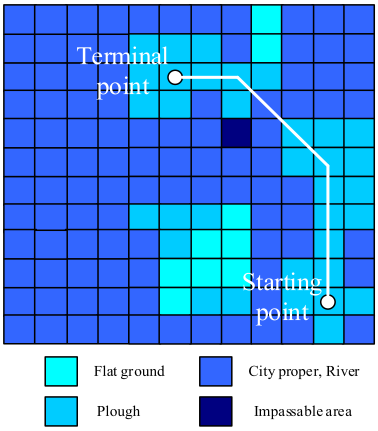


Fig. 7 Results of transmission line path planning

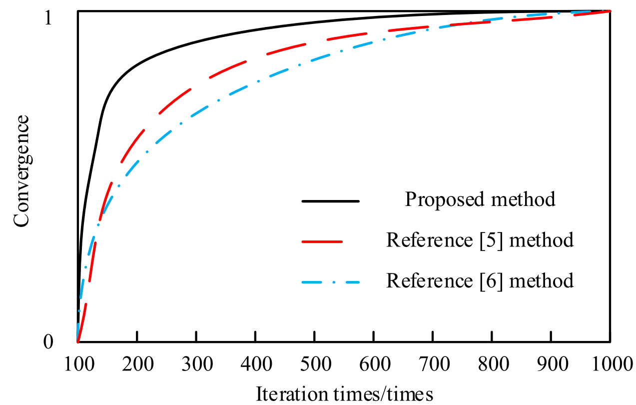


Fig. 8 Algorithm convergence degree

As can be seen from Fig. 7, the transmission line path is automatically planned by using this method, and the impassable area is successfully avoided, and the redundant corners are removed in the feasible area, and a transmission line path with low cost and low construction difficulty is automatically planned, which shows that this method is effective.

Performance Analysis

In summary, literature (Tao et al., 2022) and literature (Xie Jinghai et al., 2020) were selected as the comparison methods for the proposed methods, and the algorithm convergence, transmission line planning time, planning results, and planning accuracy were used as comparison indicators to test the effectiveness of the proposed methods. The two reference methods were selected because they are representative in the field of transmission line path planning and have a high correlation with the proposed methods in terms of research ideas or technical applications. Reference (Tao et al., 2022) explores the application of intelligent algorithms in digital transmission line path planning based on hierarchical reinforcement learning, and reference (Xie Jinghai et al., 2020) explores the key technologies of transmission line path planning based on improved ant colony algorithm from different perspectives. These methods are compared with the solution proposed in this paper using a ground obstacle remote sensing spatial model and ant colony algorithm. Among them, algorithm convergence is an important indicator for measuring algorithm efficiency and stability. It reflects whether the path cost tends to stabilize or reaches a predetermined threshold as the number of iterations increases during the algorithm's search for the optimal solution. For heuristic search algorithms such as ant colony algorithm, fast and stable convergence means that high-quality path planning solutions can be found within a reasonable time, reducing unnecessary waste of computing resources.

Planning time is one of the key factors in evaluating the practical application value of algorithms. Shorter planning time can accelerate project progress and improve overall efficiency. Therefore, comparing the execution time of different algorithms on the same or similar problems can intuitively reflect the practicality and efficiency of the algorithms.

The planning results directly reflect the performance and advantages and disadvantages of the algorithm. In transmission line path planning, the planning results include the length of the path, the smoothness of the path, and the avoidance effect between the path and obstacles. An excellent planning algorithm should be able to generate transmission line paths that are short in length, smooth in the path, and effectively avoid ground obstacles, thereby reducing construction costs and improving the safety and stability of power grid operation.

Planning accuracy is an important criterion for evaluating whether an algorithm can meet the requirements in practical applications. In transmission line path planning, accuracy is reflected in whether the algorithm can accurately identify and handle various ground obstacles (such as mountains, rivers, buildings, etc.), as well as whether it can accurately plan transmission line paths that comply with specifications based on actual terrain and engineering requirements. High accuracy planning results can reduce construction difficulty and risks, and improve the overall performance of the power grid.

(1) Algorithm convergence test

The convergence test results of the proposed method, the method in reference (Tao et al., 2022), and the method in reference (Xie Jinghai et al., 2020) are shown in Fig. 8.

From the analysis of Fig. 8, it can be seen that the proposed algorithm can maintain a high degree of convergence when the number of iterations is 200. When the number of iterations reaches 700, the convergence of the proposed algorithm is infinitely close to 1. From the perspective of fast convergence and stability, this algorithm can achieve high convergence with fewer iterations, which reflects its efficiency. Efficiency means that the algorithm can complete optimization tasks within a limited time, thus meeting the time constraints in practical applications.

(2) Time consumption for transmission line planning

As the area of non communicable areas in transmission lines increases, the time-consuming results of using different algorithms for transmission line planning are shown in Table 3.

According to Table 3, as the area of impassable areas increases, the time consumed by using the three algorithms for transmission line planning also gradually increases. Among them, the proposed method can control the time consumption within 16 ms. This is because the method proposed in this article improves the search efficiency and optimization capability of ant colony algorithm by introducing optimization techniques such as variable step size crossover strategy and corner processing strategy. These optimization strategies enable the algorithm to quickly find the global optimal solution during the search process, thereby reducing planning time and enabling faster implementation of transmission line planning.

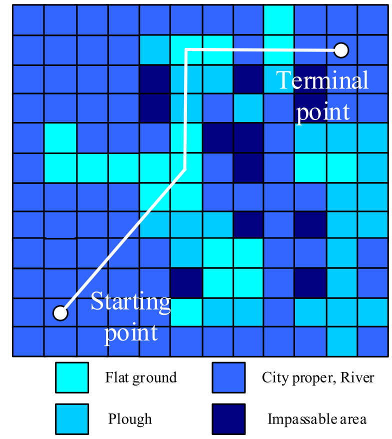
(3) Obstacle avoidance planning test

To verify the reliability of the method, the obstacle avoidance effect was tested. In the experiment, several impassable areas were set up in the transmission line planning area. And three methods were used for path planning, and the test results are shown in Fig. 9.

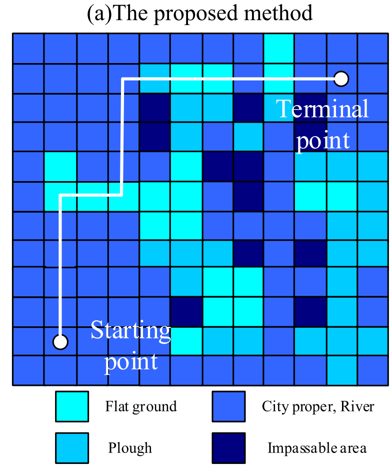
From Fig. 9, it can be seen that when using the proposed method for automatic planning of transmission lines, ground obstacles can be completely avoided and the most economical path can be selected as the

Table 3 Time consumption results of transmission line planning

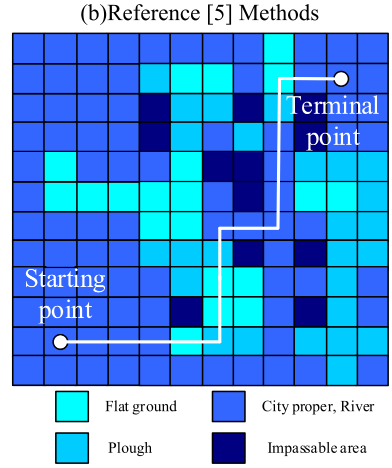
Impassable area/ m^2	The method in this paper	The reference (Tao et al., 2022) method	The reference (Xie Jinghai et al., 2020) method
10	9.75 ms	12.03 ms	13.5 ms
20	10.25 ms	12.14 ms	17.25 ms
30	11.08 ms	12.25 ms	18.5 ms
40	11.25 ms	12.5 ms	19.25 ms
50	11.33 ms	13.17 ms	19.75 ms
60	12.5 ms	14.17 ms	22.42 ms
70	13.75 ms	15.75 ms	22.67 ms
80	14.23 ms	16.67 ms	23.75 ms
90	14.56 ms	18.5 ms	25.17 ms
100	15.08 ms	19.08 ms	26.08 ms



(a)The proposed method



(b)Reference [5] Methods



(c)Reference [6] Methods

Fig. 9 obstacle avoidance effect diagram of this method

transmission line path. Therefore, it can be seen that the ground obstacle spatial model constructed by this method based on preprocessed data can accurately reflect the terrain, topography, and distribution of obstacles. This model not only improves the accuracy of path planning, but also makes the planning process more realistic, resulting in good obstacle avoidance and high reliability in the process of transmission line path planning.

(4) Planning accuracy testing

In order to further verify the accuracy of this method, the accuracy of path planning is taken as the measurement index, and 1000 sample paths are taken as the research object, and the accuracy of path planning of different methods is analyzed, and the method of reference (Tao et al., 2022) and the method of reference (Xie Jinghai et al., 2020) are used as the comparison methods. The results are shown in Table 4.

From the data in Table 4, it can be seen that the planning accuracy of the proposed method is over 98%, while the planning accuracy of the reference method is relatively low. Among them, the planning accuracy of the reference (Tao et al., 2022) method is only 98.3%, and the planning accuracy of the reference (Xie Jinghai et al., 2020) method is only 96.6%, which is more than 1.6% lower than this method. This is because the ground obstacle spatial model constructed based on preprocessed data can accurately reflect the distribution and characteristics of obstacles such as terrain, landforms, vegetation, and buildings. This refined model not only improves the accuracy of path planning, but also enables planning algorithms to more accurately evaluate the feasibility and cost-effectiveness of different paths, thereby selecting the optimal path. Therefore, the planning accuracy of the method proposed in this article is relatively high.

Conclusion

With the rapid development of the economy and the continuous deepening of the energy security strategy, power grid construction is facing greater challenges. In order to make the power grid run safely and smoothly, it is very important to plan the transmission line path scientifically and reasonably. Therefore, this paper proposes a digital transmission line path automatic planning method based on the ground obstacle remote sensing spatial model and ant colony algorithm. Based on the spatial model of ground obstacles, this method uses the improved ACO algorithm to automatically plan the transmission line path. Through algorithm optimization and automatic iteration, planning efficiency can be significantly improved, labor costs can be reduced, and more complex and variable geographical environments and constraints can be handled. Especially when planning thousands of kilometers of transmission lines, the advantages of automation methods are particularly evident. Regarding the cost issue of unmanned aerial vehicle (UAV) coverage, its efficiency, flexibility, and accuracy should be comprehensively considered, as well as its long-term impact on improving overall project efficiency and safety. Experiments show that this method has a good performance in automatic transmission line path planning, and is suitable for solving such problems. Compared to drone datasets, satellite datasets can cover a wider geographical area and contain more diverse geographic environments. By applying algorithms to satellite data, their performance can be further examined under different terrain, climate, and ecological conditions. This helps to determine whether the method can still effectively construct ground obstacle models, accurately assess costs, and plan reasonable transmission line paths in the face of complex and changing geographical conditions on a global scale, thereby providing a more solid basis for its widespread application in practical engineering and ensuring the reliability and universality of the method without being limited by data sources.

However, this method also has limitations, such as insufficient consideration of environmental and social factors, inadequate assessment of special impacts in ecologically sensitive or densely populated areas, and difficulty in balancing complex environmental constraints when crossing ecologically diverse areas, which may result in the inability to obtain the optimal path. Further improvement of multi-objective optimization strategies is needed to address these shortcomings. Future research focuses on multiple aspects to enhance the performance of the method. On the one hand, the deep integration of machine learning technology is a key direction, such as using the powerful feature learning capability of deep learning to automatically extract more complex and representative features of ground obstacles and further optimize the remote sensing spatial model of ground obstacles, so as to improve the accuracy of path planning. On the other hand, in terms of algorithm optimization, we can explore combining the advantages of other intelligent optimization algorithms and forming a more efficient hybrid algorithm with the ACO algorithm to enhance the ability to search for the optimal path and reduce the computation time. At the same time, strengthen the integration research with multi-source data, in addition to remote sensing data,

Table 4 Planning accuracy

Sample data/strip	Planning accuracy/%		
	The method in this paper	The reference (Tao et al., 2022) method	The reference (Xie Jinghai et al., 2020) method
200	99.7	97.5	96.5
400	99.3	98.0	95.0
600	99.0	98.0	95.8
800	98.9	98.0	96.4
1000	98.6	98.3	96.6

incorporate meteorological, geological and other data, comprehensively consider more influencing factors, so that the planning results are more in line with the actual engineering needs, and comprehensively improve the efficiency and practicability of the path planning method of transmission lines, to better serve the construction of the power system.

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Declarations

Conflicts of interest The authors declared that they have no conflict of interest.

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