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Cable Laying Path Planning Based on Optimized Ant Colony Algorithm

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Abstract. To address the large error and low efficiency of traditional manual design in cable laying task, the computer-aided design optimized by Ant Colony Algorithm (ACA) is applied to cable laying path planning. The shortest path for cable laying is solved via the ACA's multi terminal path calculation for complex path planning. Furthermore, the planarized cable laying path is optimized via Gompertz function in aspects of pheromone restriction and self-adaptive adjustment of volatilization factor, thus improves the ACA in both convergence speed and global performance. The simulation results show that the optimized ant colony algorithm can quickly obtain the shortest cable laying path in the task of substation digital 3D cable laying, which saves the cost of manpower and materials, and improves the design accuracy.

AMS subject classifications: 68Q25, 78M50

Key words: Ant colony algorithm (ACA), Cable laying, Pheromone, Volatilization factor, Convergence rate.

1 Introduction

In order to adapt to the rapid development of China's economy and people's growing demand for electricity, power enterprises need to increase the scale and speed of grid construction. Among them, cable laying is a key basic link and one of the most complex parts of power plant construction [1]. In the past, the traditional manual design scheme

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was based on two-dimensional design drawings or Auto CAD software for cable laying and on-site cable length calculation. However, due to the large errors and waste caused by manual statistics of cable consumption and calculation of cable length summary, it is difficult to meet the needs of modern engineering. As the number of cables laying increases year by year and the diversified needs of cable laying methods, how to realize the unification of cost saving and efficient laying has become a key problem to be solved at present [2].

Based on the above problems, three-dimensional digital aided design technology of computer is considered to be applied to cable laying design [3]. The core of the cable laying system is the algorithm to calculate the cable path [4-6], and the commonly used algorithms include Dijkstra's algorithm [7], particle swarm optimization algorithm [8] and dynamic programming algorithm. The application of traditional algorithm to heuristic intelligent algorithm in cable laying is conducive to the accurate and efficient planning of cable laying path. Literature [9] proposed an improved Dijkstra algorithm in terms of channel capacity limitation and reducing the number of turns, which was applied to the cable laying of pumped storage power stations and reduced the operation time. Literature [10] applies A-Star algorithm to the laying of cable shortest path, which reduces the workload of designers and improves economic benefits. Literature [11] applies the idea of hierarchical sequence method to the cable laying model. Genetic algorithm and Dijkstra algorithm are combined to solve the shortest path of cable laying. However, this algorithm can only solve the path between two devices and cannot consider the cable laying between multiple device nodes. Literature [12] uses tree and mesh search algorithms to accurately calculate the path and length of cables, but the algorithm is simple in structure and not suitable for large-scale complex power grids.

Aiming at the problems of local optimization and slow convergence in the application of traditional ant colony algorithm to cable laying design, this paper optimizes the algorithm and limits its pheromones to a certain range to avoid abandoning poor paths in the early stage of the algorithm. At the same time, the volatile factors are adjusted adaptively with Gompertz growth function to improve the convergence speed of the algorithm. When the optimized ant colony algorithm is applied to cable laying, it can get the shortest cable laying length in a shorter time, improve the accuracy of algorithm iteration, reduce the pause phenomenon in the algorithm running process, and improve the cable laying efficiency and quality.

2 Cable laying

In order to meet the needs of power grid development and transmission capacity, more and more cables and high-voltage cables are put into use. In the process of cable laying, cables of different sizes need to be placed on the support according to the laying rules, as shown in Figure 1. Circles represent cables of different diameters and types, and the actual cable conditions required by each layer of the support are different.

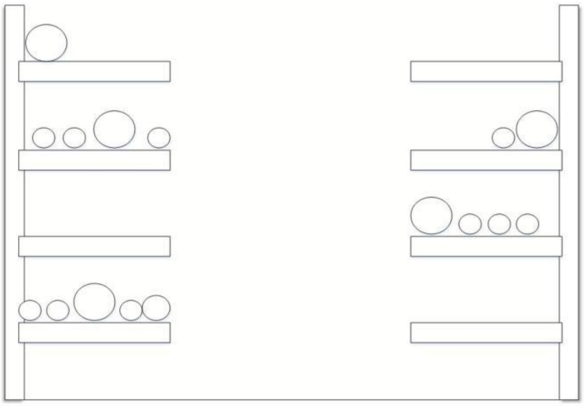

Figure 1: Cable support diagram

Cable is the carrier of information and current transmission, with strict internal structure. As shown in Figure 2, the cable consists of an insulating layer, a protective layer and a wire core, etc. The wire core is the conductive part of the cable, and the insulation layer electrically isolates the wire core from the earth and the different phases of the wire core.

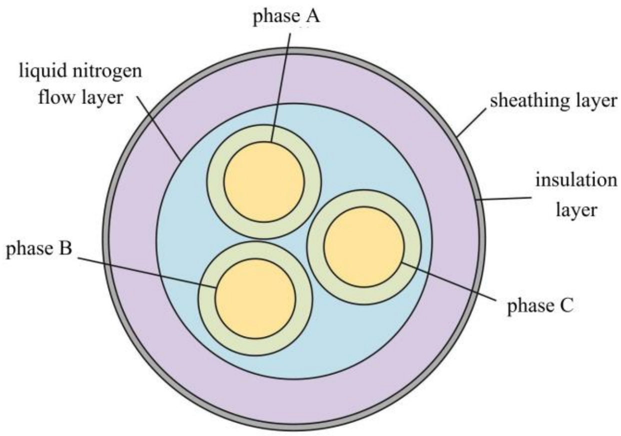

Figure 2: Cable section diagram

Cable laying is the process of laying and installing cables along the survey line to form cable lines. Auxiliary supporting facilities such as bridge and cable trench need to be installed in advance. There are various laying methods such as row pipe laying, direct buried laying, and vertical laying. There are many types of cables, such as medium voltage cables, low voltage cables, and control cables. Electrical engineering design may require multiple types of cables, but it is worth noting that only the same type of cable can be laid in a channel, and the floor area ratio of the channel should be considered to retain sufficient margin for subsequent maintenance work [13]. The core requirement of cable laying is that the cable laying path meets the engineering design requirements and the length is shortest, so it is necessary to introduce the core algorithm of cable laying.

Cable laying is a complex project (Figure 3). Before laying, it is necessary to carry out a variety of tests such as insulation resistance and voltage resistance. During laying, factors such as the surrounding environment and cable length should be considered.

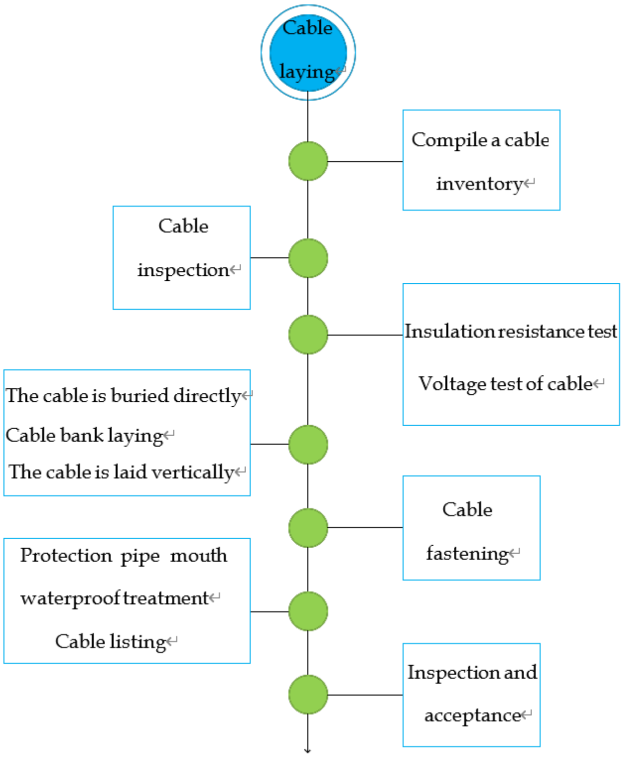

Figure 3: Cable laying flow chart

3 Ant colony algorithm

3.1 Principle of ant colony algorithm

Ant Colony Algorithm (ACA) is a bionic intelligent algorithm with features such as distributed computing, positive information feedback and strong robustness, and can be integrated with other algorithms [14]. The study found that the ants release a biological hormone called pheromone along the path, and retain it for a period of time and continue to evaporate, the ants can sense this hormone, and will have a higher probability of choosing the path with a higher concentration of pheromone. Pheromones with longer paths volatilize relatively more, and those with shorter paths volatilize relatively less. The next ant has a higher probability to choose the path with more pheromones, and so on, more and more ants walk on the shorter path, and the optimal path is obtained [15-18], as shown in Figure 4.

From point N to point M, there are four paths, such as $NBAM$, NBM, $NCBAM$, and $NCBM$. The first ant randomly chooses the $NBAM$ path to point M. With the increase of the number of ants going out for food, ants pass through all four paths and leave pheromones that will evaporate with time. As pheromones volatilized and increased, more and more pheromones were found on the shortest path NBM, and at the same time, more and more ants chose this path, and eventually all ants found the shortest path.

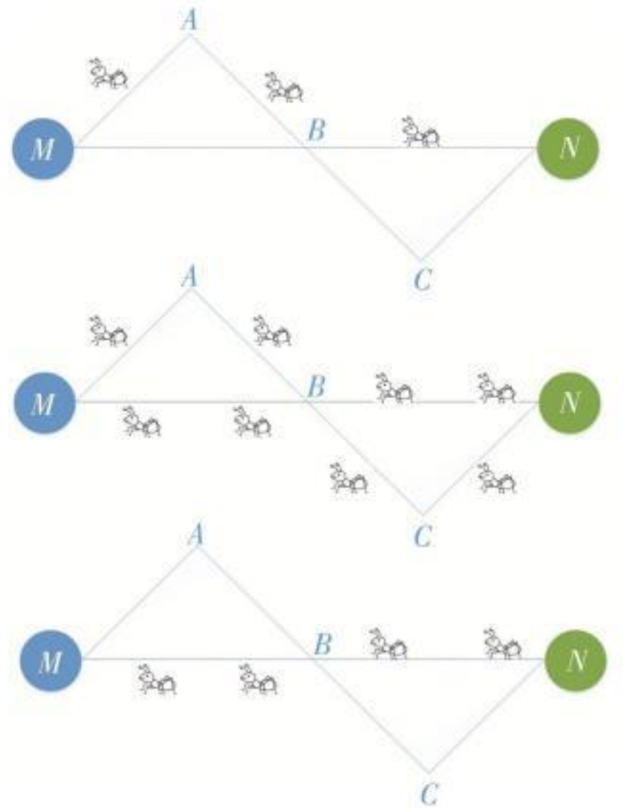

Figure 4: Biological model of ant colony algorithm

3.2 Mathematical model of basic ant colony algorithm

In the mathematical model of ant colony algorithm, there are the following assumptions: 1) All ants have the same foraging speed; 2) During the foraging process, all ants release the same pheromone at the same time [19].

In the ant colony system, N is generally used to represent the number of all nodes $C = \{1,2,3,\cdots,n\}$ that exist in the process of ants from the beginning to the end of the foraging process, and M is used to represent the total number of ants in the whole system. When an ant is at node i, the probability of the next move to node j is expressed by the transition probability：

$$p_{ij}^{k}(t) = \begin{cases} \frac{[\tau_{ij}(t)]^{\alpha} \cdot [\eta_{ij}(t)]^{\beta}}{\sum_{s \subset \mathrm{allowed}_k} [\tau_{is}(t)]^{\alpha} \cdot [\eta_{is}(t)]^{\beta}}, & j \in \mathrm{allowed}_k, \\ 0, & j \notin \mathrm{allowed}_k, \end{cases} \tag{1}$$

where: $p_{ij}^{k}(t)$ represents the probability of the ant moving from node i to node j at time t; $\mathrm{allowed}_k$ represents the set of all nodes except those that the k-TH ant has already walked through; α represents the influence factor of pheromone, reflecting the relative importance of the amount of pheromone accumulated on the path during ant movement in guiding ant colony search. β represents the visibility factor, reflecting the relative importance of heuristic information in guiding ants to search. $\tau_{ij}(t)$ represents the pheromone concentration between node i and node j, which will volatilize and update with time; $\eta_{ij}(t)$ is the visibility value, which refers to the ant's visual range, that is, the ant on node i, the visibility of the next node j:

$$\eta_{ij} = \frac{1}{d_{ij}}, \tag{2}$$

where, d_{ij} represents the distance between node i and node j. The smaller d_{ij} is, the greater the visibility value η_{ij}, so the greater the transition probability $p_{ij}^{k}(t)$, that is, the greater the possibility that the k ant chooses node j at node i.

Ants will leave pheromone on the path and continue to volatilize, and when the backward ants pass by the same path, they will also leave pheromone and continue to volatilize, so $\tau_{ij}(t)$ will change with time, and formula (3) is its updated expression:

$$\tau_{ij}(t+1) = (1-\rho)\cdot\tau_{ij}(t) + \sum_{m=1}^{N}\Delta\tau_{ij}^{m}(t), \tag{3}$$

among them, ρ is the volatile factor of pheromone, indicating the attenuation degree of the information left by the ants between nodes i and j. The greater the value, the less the influence of the information left by the former ants on the latter ants, and vice versa, the greater the value. The value of ρ is generally a constant between 0 and 1. $1-\rho$ represents the residual pheromone. ρ is introduced mainly to avoid the failure of some poor path pheromone and affect the optimization of the path of the subsequent ants. $\Delta\tau_{ij}^{m}(t)$ represents the pheromone left between node i and node j during the iteration of the m ant, and there are three updating modes. It corresponds to three models: Ant-Cycle model, Ant-Quantity model and Ant-Density model. The ant cycle model is generally chosen, and its expression is

$$\Delta\tau_{ij}^{m}(t) = \begin{cases} \frac{Q}{L_m}, \text{The m-th ant goes from node i to node } j, \\ 0, \quad \text{other}, \end{cases} \tag{4}$$

where: Q is the pheromone enhancement coefficient, indicating the degree of influence of pheromone-on-pheromone renewal, and is a constant; L_m is the length of all paths taken by the m ant during the current iteration.

4 Cable laying based on optimized ant colony algorithm

4.1 Modeling of cable laying problems

In order to apply ant colony algorithm to cable laying, it is necessary to abstract the cable channel of substation. The equipment connecting the screen cabinet and the power distribution device and the intersection of the cable connection are equivalent to one node. The side between the two nodes represents the cable, and the side weight represents the length of the cable. There are two kinds of distance between two nodes: the Euclidean distance and the Manhattan distance [5]. Assuming $P_1 = (x_1, y_1, z_1)$ and $P_2 = (x_2, y_2, z_2)$, the Euclidean distance refers to the actual distance between two nodes:

$$D_1 = \sqrt{(x_1-x_2)^2 + (y_1-y_2)^2 + (z_1-z_2)^2}. \tag{5}$$

The cable is laid along the cableway, not necessarily the actual distance between the two points, but the Manhattan distance. The Manhattan distance is the sum of the absolute distances of two nodes on the xyz axis:

$$D_2 = |x_1 - x_2| + |y_1 - y_2| + |z_1 - z_2|. \tag{6}$$

4.2 Optimization of ant colony algorithm

Cable laying is also a path optimization problem [6]. The application of traditional ant colony algorithm to cable laying has certain defects: the initial pheromone of traditional ant colony algorithm is the same, the probability of selecting the next node is random, and it takes a long time to form positive feedback, resulting in slow convergence speed. If the initial pheromone is updated with positive feedback to the suboptimal solution, it is easy to have premature convergence and fall into local optimal. Therefore, this paper optimizes the traditional ant colony algorithm [15-16].

4.2.1 Pheromone limitation

In the process of route selection, ants will preferentially choose several better paths. If the remaining paths have not been passed by ants for a long time and the pheromone has evaporated, the algorithm will stall. In this paper, two pheromone bounds τ_{max} and τ_{min} are introduced into the algorithm:

$$\tau_{min} \leq \tau \leq \tau_{max}, \tag{7}$$

limiting the pheromone in each iteration of the algorithm to this range can improve the stagnation phenomenon.

4.2.2 Volatile factor adaptive adjustment

Pheromone is the core of traditional ant colony algorithm, and the volatile factor ρ plays a key role in pheromone. When the pheromone volatile factor is too small, there is little difference in the pheromone concentration in the early stage, and the reliability of the branch route selection is reduced, it takes longer time to select the optimal path, and the algorithm convergence time is longer. When the pheromone volatile factor is too large, the pheromone on the more complex path will gradually volatilize to 0, and the algorithm is easy to fall into local optimal. Therefore, the Gompertz growth function is introduced to adaptively adjust volatile factors, as shown in Figure 5.

Gompertz model is generally used in actuarial science and bacterial growth curve modeling, is an increasing function, at the beginning with the increase of time, the ρ value growth rate is fast, reach a certain point in time, the growth rate becomes slow, and then the ρ value will gradually approach a limit value α. Gompertz function:

$$\rho = \alpha e^{-e\beta - \gamma x}, \tag{8}$$

the lower limit of the function is 0, the upper limit is α. β is the growth rate, γ is the growth rate, both of which are related to the speed of change of the function dependent variable. In this paper, the Gompertz function is applied to the adaptive adjustment of volatile factor ρ, and the number of iterations t is taken as the independent variable. In the early stage of the algorithm, the volatile factor is small, and the guiding ability of the algorithm is weak, which is conducive to global search and improve the accuracy of the algorithm. As the number of iterations increases, the volatile factors gradually increase, and the convergence speed of the algorithm also increases. In the face of different environments, the function coefficients α, β, γ can be set by themselves to improve the flexibility of the algorithm.

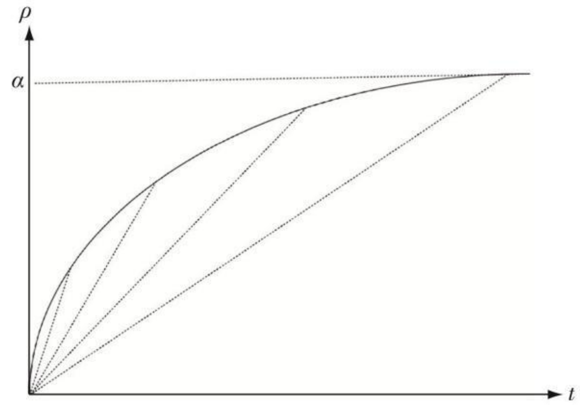

Figure 5: Gompertz function

4.2.3 Optimization of ant colony algorithm implementation

For the cable laying problem, the steps of ant colony algorithm [17-20] are as follows.

1) Data processing of substation equipment and node coordinates.

2) Parameter initialization. The number of ants M, total number of iterations N, pheromone influence factor α, visibility influence factor β and other parameters in the ant colony system were set.

3) Place all ants evenly on the initial device of path optimization, and record the initial node in the path table.

4) Calculate the probability of selecting the next node with formula (1), and select the next node with roulette. If a dead end is encountered, start again step 2), otherwise the next node will be recorded in the path table.

5) The pheromone was updated using formula (3), and the number of iterations was $N_c + 1$.

6) If the number of iterations $N_c < N$, go to step 2).

7) Output the optimal path solution.

The algorithm flow is shown in Figure 6.

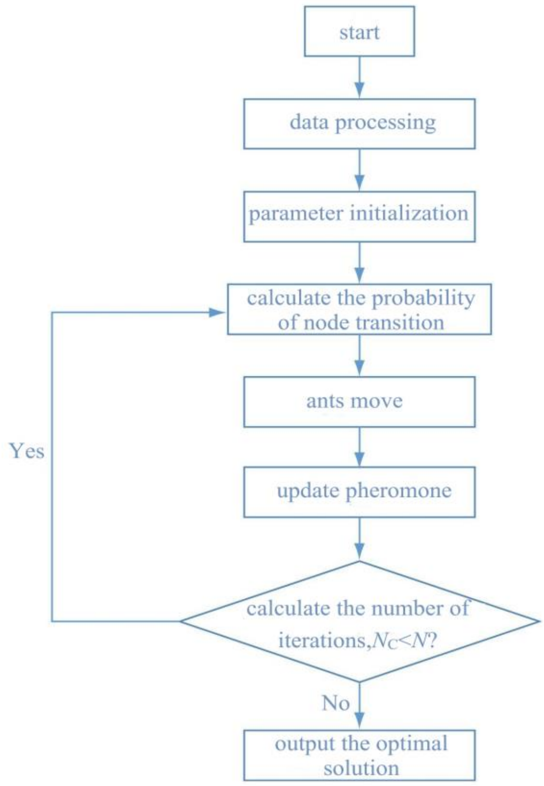

Figure 6: Flow chart of ant colony algorithm

5 Algorithm simulation test

In order to verify the effectiveness of the optimized ant colony algorithm in cable laying, a program was written based on Matlab software to project the three-dimensional cable path diagram of the substation into a two-dimensional diagram for analysis, and the cable path plane as shown in Figure 7 was built by using data such as cable channels and node coordinates. Among them, the simulation parameter Settings are shown in Table 1.

Table 1: Simulation parameters

algorithm parameters	symbol	value
pheromone influencing factor	α	1
visibility influencing factor	β	5
total number of ants	M	50
number of iterations	N	100
pheromone intensity	Q	1
maximum volatility coefficient	ρ_{max}	0. 6

Considering the diversity of cable laying path selection and the tree structure between device nodes, the optimal path selection between devices is carried out with the advantage of optimized ant colony algorithm in the selection of optimal path tree. Floyd algorithm can also be used to find the shortest path for cable laying, but it can only calculate the path length of two endpoints, which has its inherent limitations. Compared with Floyd algorithm, the optimized ant colony algorithm is more suitable for complex lines, which can not only lay cables between two endpoints, but also lay cables at multiple endpoints.

5.1 Path optimization example analysis

In the cable path plan, select any two device nodes, such as device 3 and device 7. There are three paths between the two nodes, and the route $L_k = 117$ obtained by optimizing ant colony algorithm is shown in Figure 8. It is proved that this route conforms to the principle of optimal route and meets the initial requirements of cable laying.

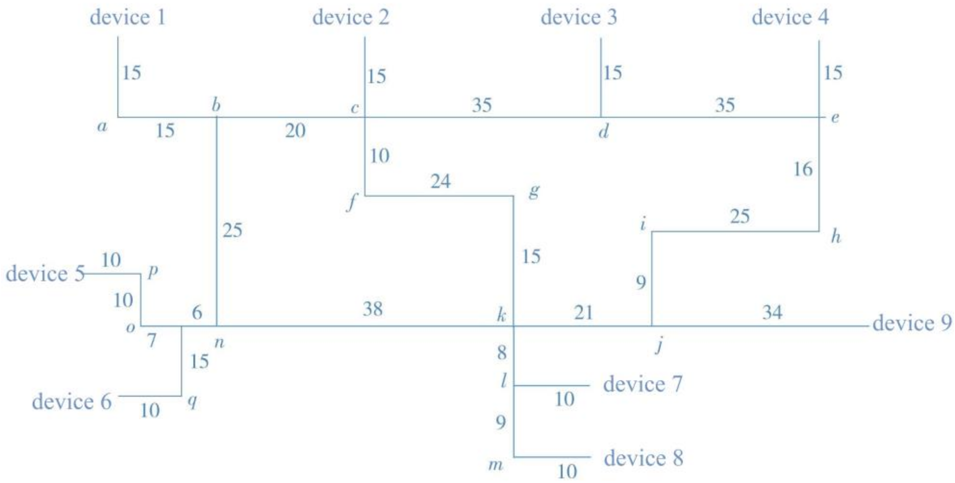

Figure 7: Cable path planning

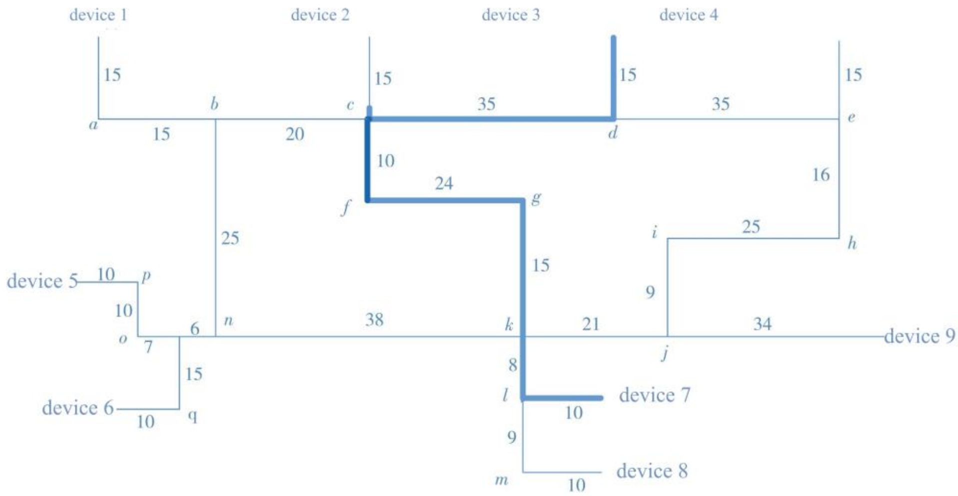

Figure 8: Cable path optimization plan for two equipments

Select three devices at random for laying and find the shortest path among them. As shown in Figure 9, devices 1, 3 and 7 have a variety of laying paths, each of which has different lengths. The result of optimized ant colony algorithm is $L_k = 167$, which is verified to meet the requirement of shortest path.

Four devices are randomly selected for laying and the shortest path is found. As shown in Figure 10, devices 1, 3, 7 and 9 have a variety of laying paths, each of which has different lengths. The result of optimized ant colony algorithm is $L_k = 222$, which is verified to meet the requirement of shortest path.

5.2 Comparative analysis of numerical examples

On the basis of the cable path plan, the traditional ant colony algorithm and the optimized ant colony algorithm are used to run multiple path optimization programs. In the face of simple and uncomplicated paths, the traditional ant colony algorithm can obtain the shortest path in the actual situation, but there will be local optimal or even stagnation when running the path in complex cases such as many cross lines. As shown in Table 2, thirty experiments were conducted in total, and the local optimal rate of the traditional ant colony algorithm was 16.67%, with stagnation occurring for four times. After optimization, the local optimal rate of ant colony algorithm is 3.33%, and only one stagnation occurs. It can be seen that the improved algorithm can greatly optimize the program operation and find the shortest path for the cable.

As shown in Figure 11, the ant colony algorithm was used to run 10, 20, 30 and 40 times before and after optimization, regardless of pheromone concentration limit, and the average value of the total time of multiple runs was recorded and calculated. The average time of the traditional ant colony algorithm running 30 times is 0.251 s, and the optimized ant colony algorithm is 0.147 s. It can be seen that compared with the traditional ant colony algorithm, the optimized ant colony algorithm with Gompertz model has shorter iteration time and faster convergence speed.

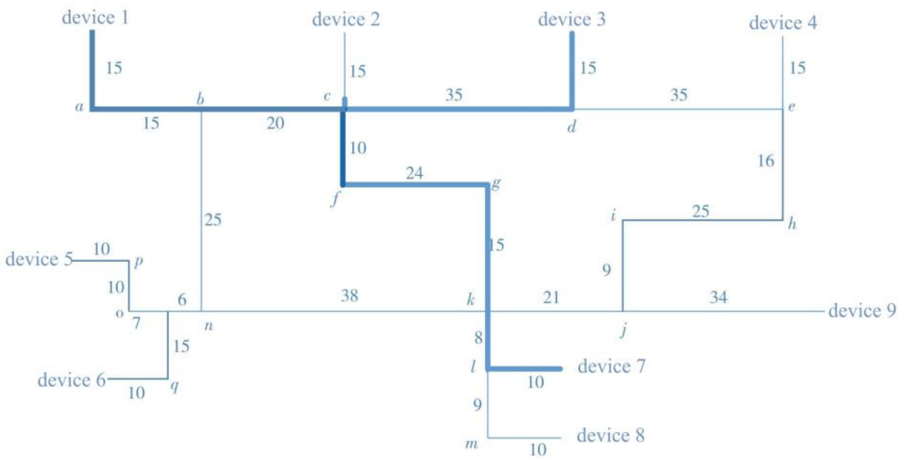

Figure 9: Cable path optimization plan for three equipments

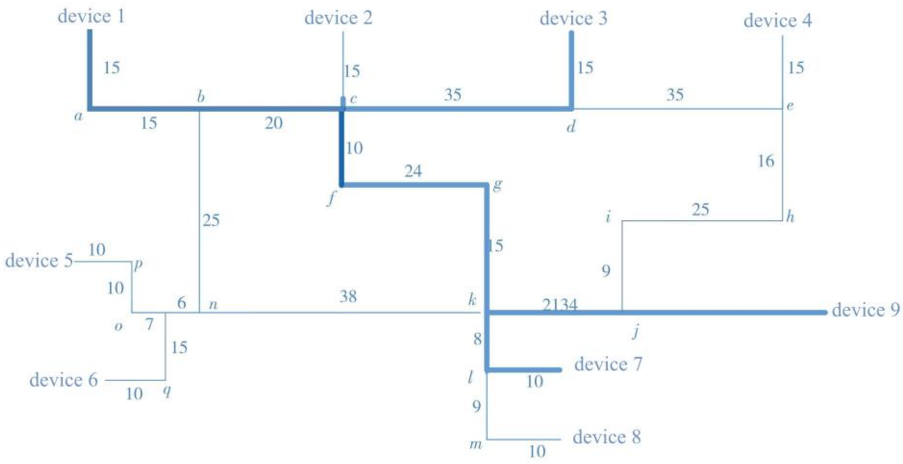

Figure 10: Cable path optimization plan of four equipments

Table 2: Comparison of ACA's local optimization before and after improvement

number of tests	traditional ant colony algorithm		improved ant colony algorithm	
	stagnation frequency	local optimal rate/%	stagnation frequency	local optimal rate/%
10	1	20	0	0
20	3	15	0	0
30	4	16. 67	1	3. 33
40	5	20	1	2. 5

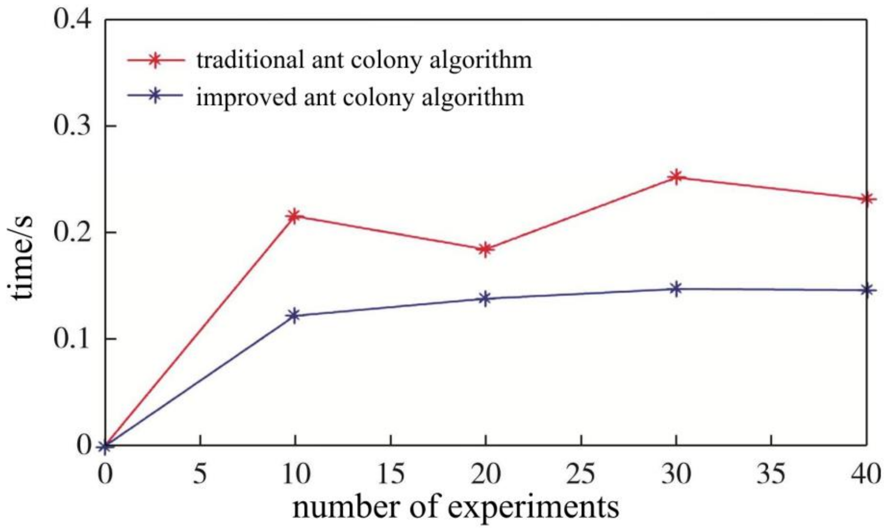

Figure 11: Comparison of iteration time

6 Conclusions

The optimal ant colony algorithm is applied to the cable laying design based on the computer 3D digital auxiliary cable laying platform, and the cable laying path is precisely planned. In this paper, the specific process of cable laying and the mathematical model of optimizing ant colony algorithm are given. In view of the problems existing in the application of traditional ant colony algorithm in cable laying, the ant colony algorithm is optimized and improved in two aspects of pheromone and volatile factor. Experiments show that the optimized ant colony algorithm can achieve global optimization, and the convergence speed is faster, which improves the effectiveness of cable laying.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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