Task Planning of Space Maintenance Robot Using Modified Clustering Method

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ABSTRACT

This paper investigates the on-orbit maintenance task planning of large-scale space solar power station. The research is of great significance for the normal operation of large-scale space equipment. Space robots are very maneuverable, which makes space maintenance possible. A new task planning algorithm is proposed for the on-orbit maintenance of space robots. Firstly, based on the discretization method, the modified clustering method is used to cluster the maintenance area of large-scale space solar power stations. Secondly, the hierarchical structure principle is used to assign tasks to the space robot, the inner layer plans the shortest path within the cluster set, and the outer layer plans the optimal path between the cluster sets. Finally, based on the optimal path of the outer layer of the maintenance task, a hybrid optimization algorithm based on tabu algorithm and modified ant colony algorithm is proposed. The algorithm can meet the space machine task allocation requirements and analyze the maintenance path under certain energy conditions. The simulation results show that the proposed algorithm can effectively solve the optimal problem of space robot mission planning under resource constraints.

INDEX TERMS

Space robot, task clustering, hybrid optimization algorithm, task planning.

I. INTRODUCTION

On-orbit maintenance technology is one of the classic research topics in the field of space mission planning, which is very important for the aerospace industry. The development of space robot mission planning technology can provide technical support for future on-orbit maintenance tasks. Some large space structures, such as space telescopes and Space Solar Power Station, are important directions for future space development. Sending a telescope into Earth orbit is one of the hallmarks of success in the space age. The “Hubble” and “Kepler” space telescopes had completely changed astronomy, and the ultra-large-scale telescopes [1], [2] are a major trend in future space development. Since Glaser [3] proposed Space Solar Power Stations, it has attracted worldwide attention, and various space powers have proposed many related concepts [4]–[7]. The Space Solar Power Station (SSPS) [8], [9] is a huge energy system that collects and converts solar energy into electricity in space and then wirelessly transmits it to the Earth [10]. SSPS has the potential for higher energy efficiency than terrestrial solar systems.

Space Solar Power Stations and ultra-large-scale telescopes are characterized by large size and many parts. The life expectancy of these large space equipment will reach several decades, but the service life of some parts is still far behind. The maintenance of space equipment is also facing enormous challenges. At present, there are few studies on space maintenance, and space operations are mostly completed by astronauts and space robots. Astronauts work in outer space with high risk factors and high economic costs, therefore, the main maintenance work of ultra-large-scale space structures in the future requires space robots to complete [11]. At present, there are many scholars studying the assembly of ultra-large-scale space institutions. Cheng et al. [9] proposed an assembly scheme that uses the space robot to realize the SSPS concept of the platform. The improved artificial potential field method is used to obtain the best route for transporting the assembled module to its operating position while avoiding obstacles. She et al. [12] proposed a combination of branch and bound method and improved ant colony algorithm to solve the problem of on-orbit assembly task.
planning by considering the minimum attitude perturbation criterion and topological constraints. Gabrel and Murat [13] proposed an integer programming model based on mathematical programming and graph theory. The task planning problem is expressed as a weighted directed acyclic graph G, and the path of G is taken as the solution to the problem.

Space robots play an important role in assembly and maintenance tasks, in recent years, considerable progress has been made in the study of space robot mission planning [14]–[17], which laid the foundation for on-orbit assembly and maintenance of large space agencies. Space robots can identify each task and perform tasks autonomously, which can greatly reduce the dependence of assembly tasks. Space robots also have great advantages over astronauts in space activities [18], [19]. The space robot mission planning plays an important role from the task determination to the final execution process. The task planning process takes the state of the space robot and the planning goals as inputs, and obtains a set of space robot action sequences through a certain decision method, the space robot space robot according to the sequence to achieve the task of planning objectives. Lillie proposes the concept of using a single robot assembly task and discusses issues related to future space-on-orbit assembly and subsequent on-orbit services [20]. Chen proposed an improved autonomous assembly path planning algorithm that considers collision avoidance constraints, ensuring assembly flexibility [21]. Oegerle et al. proposed a scalable space observatory design concept that describes how these individual components are packaged and launched by heavy-duty launch vehicles, and how space robots and astronauts assemble telescopes with these components [22]. Hu solved the formation control problem of four robots in orbit assembly by proposing an adaptive sliding mode controller [23].

Through further analysis of the on-orbit assembly task planning algorithm of space robot, the assembly problem of space robot is solved, but the problem of space maintenance is not involved. When the space robot assembly method is used to solve space maintenance tasks, there exist the following problems: it is difficult to solve large-scale programming problems; the maximum number of tasks completed by the space manipulator when the energy is fixed is not considered; the difference in energy consumption between robot base movement and robot joint movement is not considered. Based on the above analysis of the current research situation, we take the Space Solar Power Station as the research object and the space robot on-orbit maintenance as the engineering background, a new method is proposed to solve the problem of space robot task planning. Cluster analysis is performed on a set of maintenance data, and the clustered tasks are assigned to the space robot, and the space robot is assigned tasks based on the hierarchical structure, the inner layer uses simulated annealing to solve the shortest path in the cluster set, and the outer layer uses hybrid optimization algorithm to solve the optimal path of maintenance, then the method of maintenance task planning is studied.

The rest of the paper is organized as follows: Section 2 introduces the basic mission background and theoretical basis. Section 3 presents a hybrid optimization algorithm and a detailed description of the algorithm. In Section 4, the accuracy and effectiveness of the proposed algorithm are verified by experiments, and the results are introduced and discussed. Section 5 gives the conclusion.

II. THEORY BACKGROUND

A. SPACE SOLAR POWER STATION MODEL

The Space Solar Power Station (SSPS) is a space power system. The electric energy is generated by a solar array. It converts solar energy in space into electrical energy and transmits the electric energy to the ground receiving station in a certain way, which can solve the earth’s energy crisis problem. The Space Solar Power Station has a long service life, in the case of high radiation and large temperature changes in space, it is very easy to cause damage to parts, so some parts need to be replaced and repaired in time.

The Space Solar Power Station had proposed many models so far, so we only consider the maintenance of space solar power station by space robot and simplify the space solar power station. SSPS itself is a large-scale energy generator, so it provides energy support for space robots through SSPS. The maintenance area on the solar power station is divided into grids, and the nodes on the grid are the central position of the maintenance points. By meshing the target areas, the regional targets can be transformed into a set of points, and then as a planning target input. In order to achieve a detailed analysis of the problem, the following coordinate system is defined, as shown in Figure 1, the Space Solar Power Station system \( O_b - X_bY_bZ_b \), with the origin of the coordinate system located at the centroid of the space solar power station, and the electrical energy generated by two continuously rotating solar arrays. The left and right coordinate systems of the solar array are \( O_l - X_lY_lZ_l \) and \( O_r - X_rY_rZ_r \), the geometric center position of the solar panel is its coordinate origin, the coordinates of all solar panels are known, and are fixed in the left and right coordinate system, in which the planning process of the maintenance path is performed.

The definition of coordinate transformation is as follows

\[
\vec{v}_b = hR_r \cdot \vec{v}_r
\]

\( hR_r \) represents the rotation matrix from coordinate system \( r \) to coordinate system \( b \). \( \vec{v}_r \) is a vector represented in the coordinate system \( r \), and \( \vec{v}_b \) is a vector represented in the coordinate system \( b \).
B. CLUSTERING ALGORITHM

Cluster analysis aims to divide a set of data points into multiple clusters by using different methods [24]. Clustering means that data points in the same cluster are as similar as possible, while data points in different clusters are as different as possible. If two or more tasks can be combined and assigned to the space robot, they are said to satisfy the clustering relation. According to the maintenance target, in the previous research, the researchers mostly used a single point target as the research object. As the number of tasks increases, the number of planned candidate solutions shows an increase in geometric progression, and the planning system bears a large amount of computational burden with limited computing power. If clustering method is used, clustering similar points together, clustering multiple point tasks into regional tasks, and then assigning tasks to space robots between clusters, thus saving time and reasonable arrangement space robots.

III. METHOD

A. MODIFIED CLUSTERING ALGORITHM

The motion of the space robot is divided into the movement of the satellite base and the movement of the mechanical arm. For the operation and the maintenance point, when the base is fixed, considering the span space of space robot, it only needs to operate the arm in a small range to complete the maintenance task, and there is no need to move the base of the space robot. Hierarchical planning ideas can effectively reduce the planning complexity and shorten the planning time. The task clustering method including hierarchical planning can make the cluster structure set the number of layers according to the needs of the task target. The clustering structure can set the number of layers according to the needs of the task target. Considering the actual situation of space robot maintenance, 1/2 arm development is chosen as the cluster radius, and 2 is chosen as the cluster layer to satisfy the maintenance scope of the space robot.

The position of the solar panel can be represented by the horizontal and vertical coordinates in the solar cell array coordinate system, centered on point \( P_x \), and the relative distance between point \( P_x \) and other points \( P_i \) is calculated in the solar cell array coordinate system.

As shown in Figure 2, the relative distance between the center point of the cluster set and any surrounding points is calculated in the solar cell array coordinate system. If the point \( P_x \) is the cluster center point and the distance \( \text{Dist}(x, i) \) between the point \( P_x \) and the point \( P_i \) is less than \( \text{eps} \), then Point \( P_i \) is placed in set \( \text{Cluster}_{x,1} \), as shown in equation (2), and the remaining points are analogized.

\[
\begin{align*}
\text{Cluster}_{x,k} &= \begin{cases} 
\{ P_i | \text{Dist}(i, x) < \text{eps}, \ k = 1 
\} \\
\{ P_i | P_i \in \text{Cluster}_{x,k-1}, \text{Dist}(i, f) < \text{eps}, \ k > 1 
\end{cases}
\text{Cluster}_{x,\text{area}} = \text{Cluster}_{x,1} \cup \text{Cluster}_{x,2} \cup \cdots \cup \text{Cluster}_{x,k} \tag{2}
\end{align*}
\]

Among them: \( \text{eps} \) indicates the cluster radius, and \( k \) indicates the number of clusters, which can be set according to the needs.

After the above process is completed, the point \( P_y \) that is not in the cluster set \( \text{Cluster}_{x,\text{area}} \) is selected as the cluster center point, and the above process is repeated to obtain other cluster sets. The set of regional maintenance targets clustered by the point targets is \( \text{Task} = \{ \text{Cluster}_{x,\text{area}}, \text{Cluster}_{y,\text{area}}, \text{Cluster}_{z,\text{area}}, \cdots \} \).

B. HYBRID OPTIMIZATION ALGORITHM

The planning process of the space robot maintenance path considers the two factors of the distance between the cluster points and the number of tasks in the cluster. As the task size increases, the optimization difficulty and calculation cost also increase significantly. Traditional optimization algorithms are more efficient when dealing with small-scale problems, while heuristic algorithms are more efficient when dealing with large-scale problems. The ant colony algorithm. Reference [25]–[27] is an algorithm that mimics the natural ants’ search path. Firstly, we improve the ant colony algorithm, and then propose a hybrid optimization algorithm based on the tabu algorithm and the modified ant colony algorithm [28], [29]. The main purpose of the algorithm is to quickly converge to the global optimal solution of the problem to reduce the computational cost.

1) BRANCH TRANSFER STRATEGY

A pseudo-random proportional probability model is used as a transfer rule in constructing the solution. The model additionally introduces a parameter \( q_0 \), and also uses a random variable \( q \) that is evenly distributed over the [0, 1] interval. The parameter \( q_0 \) is introduced as a probability boundary, and if the average pheromone content does not reach its intensity threshold, roulette is used for the selection of the next node. For the ant colony system, the ant \( k \) at the cluster center \( i \) selects the cluster center \( j \) as the next probability to be
accessed:  
\[ j = \begin{cases} 
\max \{ [\tau (i, u)]^a \cdot [\eta (i, u)]^b \}, & \text{if } q < q_0 \\
\text{Roulette selection probability}, & \text{else} 
\end{cases} \]  
(3)

If \( q \geq q_0 \), the selection probability is calculated according to equation (4)

\[ P^k_{ij}(t) = \begin{cases} 
\frac{\tau^a_{ij}(t) \cdot \eta^b_{ij}(t)}{\sum_{s \in \text{allowed}} \tau^a_{is}(t) \cdot \eta^b_{is}(t)}, & j \in \text{allowed} \\
0, & \text{otherwise} 
\end{cases} \]  
(4)

Among them, the storage in \( \text{allowed} \) is the center point of the cluster that has not been visited. The branching strategy is used to improve the search performance of the algorithm.

2) MODIFIED PHEROMONE UPDATE STRATEGY
In order to prevent the concentration of pheromone from being too large or too small, the pheromone is limited to \([\tau_{\text{min}}, \tau_{\text{max}}]\) and when the pheromone is updated so that the pheromone exceeds the upper bound \( \tau_{\text{max}} \) or the lower bound \( \tau_{\text{min}} \), it is adjusted to \( \tau_{\text{max}} \) and \( \tau_{\text{min}} \). Initialize the pheromone trajectory to \( \tau_{\text{max}} \). In order to make full use of the cyclic optimal solution, after each cycle, according to the path length of the ant, only the ants ranked in the top \( W \) and the global optimal ants can release the pheromone on the path.

\[ \tau_{ij}(t + 1) = (1 - \rho)\tau_{ij}(t) + \theta_1 \cdot \sum_{r=1}^{W} (W - r) \Delta \tau_{ij}^r(t) + \theta_2 \cdot \Delta \tau_{ij}^{gb}(t) \]  
(5)

\( \theta_1 \) and \( \theta_2 \) are weight coefficients, and \( \Delta \tau_{ij}^{gb}(t) \) represents the pheromone left by the global optimal ant.

3) ADAPTIVE PHEROMONE UPDATE METHOD
In order to improve the global search ability of the ant colony algorithm, the algorithm adaptively adjusts the value of the pheromone residual factor \( P \) after a certain number of steps to increase the diversity of solution. By reducing the value of \( P \), the global search ability of the algorithm can be improved, but the convergence of the algorithm is reduced. Let the initial value of \( P \) be \( P(t_0) = 1, 1 - P \) is a pheromone evaporation coefficient \( \rho \). Specifically as shown in Equation (6).

\[ P(t) = \begin{cases} 
0.95P(t - 1), & \text{if } 0.95P(t - 1) \geq P_{\text{min}} \\
0.95P(t - 1), & \text{otherwise} 
\end{cases} \]  
(6)

wherein, \( P \) is the pheromone residual factor, and \( P_{\text{min}} \) is the minimum value of \( P \).

4) PHEROMONE SMOOTHING MECHANISM
In the middle and late stages of the program, in order to improve the ability to explore new paths, a modified pheromone smoothing mechanism is proposed to increase the ability to explore new paths by increasing the probability of selecting low-intensity pheromone trajectories.

\[ \tau_{ij}^{gb}(t) = \tau_{ij}(t) + \delta(\tau_{\text{max}}(t) - \tau_{ij}(t)) \]  
(7)

Among them, \( \delta \) is the pheromone smoothing factor, \( \tau_{ij}(t) \) and \( \tau_{ij}^{gb}(t) \) are the pheromones before and after smoothing respectively. When \( 0 < \delta < 1 \), the pheromone accumulated during the running of the algorithm is not completely lost, but only weakened; when \( \delta = 1 \), the mechanism is equivalent to the reinitialization of the pheromone trajectory; when \( \delta = 0 \), the mechanism is closed.

5) MODIFIED TABU ALGORITHM
Ant colony algorithm has the defects of easy to fall into local optimal solution, many iterations and instability, we can use the memory ability and contempt criteria of the tabu search algorithm to make the algorithm have the ability to jump out of the local optimal solution and reduce the number of iterations, and improve the optimization ability of the algorithm. Because the tabu search algorithm is sensitive to the initial solution, the initial solution will directly affect the solution obtained by the algorithm. Therefore, the optimal solution obtained by the ant colony based on the pheromone concentration is used as the initial solution of the tabu search. Because of the better initial solution, the modified algorithm has fewer iterations and improves the stability of the algorithm.

C. ALGORITHM FLOW
For the spatial robot mission planning, the overall planning process is shown in Figure 3.

1. Using the improved clustering method to cluster the maintenance area;
2. Using the clustered data for hierarchical planning, the inner layer planning uses simulated annealing to find the shortest path between the maintenance points, and the outer layer uses the improved hybrid optimization algorithm to solve the optimal path;
3. The outer layer first sets the number of ant colonies, and the initial node is set to the position of the node (0, 0) where the space robot is located, calculate the number of tasks in the cluster between adjacent nodes and the distance between the cluster center points to construct a new heuristic factor;
4. The greedy algorithm is used to solve the current optimal path, and the modified ant colony algorithm is used to search to ensure that the pheromone concentration is within a certain range, and the branch transfer strategy is used to select and determine the next node to be repaired;
5. After all the ants have completed the search, the optimal path is selected as the starting path of the tabu algorithm, and the optimal path is obtained by the tabu algorithm. Update the pheromone increment with an improved pheromone update strategy based on the evaluation indicators;
6. Updating the pheromone residual coefficient using an adaptive method and using a smoothing mechanism to change the pheromone influence factor;
7. Iteratively find the optimal maintenance path and save the optimal solution.

IV. SIMULATION AND ANALYSIS

The effectiveness of the algorithm is verified by computer simulation. The simulation was implemented in Matlab 2016b with computer parameters of Intel Core i7-8750 processor, 2.20GHz CPU and 8GB RAM memory configuration. The basic parameters of the space solar power station for the simulation experiment are as follows: The size of the maintenance area is 100m × 30m, the size of the solar panel is 0.5m × 0.6m, and the total number of single-sided solar panels are 10000 pieces. The distribution of maintenance area is shown in Figure 4.

The time and energy cost of maintenance task was discussed under the optimal route, and three groups of simulation test examples were designed to verify the effectiveness of the planning algorithm.

A. CLUSTERING COMPARISON EXPERIMENT

This example takes the repair of a solar array on one side as an example, and performs task clustering for 200 repair point targets to test the performance of the algorithm. The above examples are solved under the pre-processing conditions of task clustering and task clustering.

After the point targets are clustered, the maintenance point targets are clustered into regional targets. The results of the clustering are shown in Table 1. The number is 1 point for the initial position of the space robot, and the point targets are clustered into 27 categories and 3 Noise points. First, the shortest maintenance path for simulated annealing is used internally for multi-element clustering, and then the improved optimization algorithm is used between clusters for optimal and shortest path planning.

The simulated annealing algorithm is an intelligent method with simple structure and strong robustness. Let’s select 4 spaces with more internal clustering points as an example, as shown in Figure 5, where (a) is the distance within the 4th cluster, (b) is the distance within the 5th cluster, (c) is the distance within the 12th cluster, and (d) is the distance within
In order to compare the difference between clustering and non-clustering in relatively large examples, two sets of experiments are set up to test the performance of the clustering algorithm. The comparison results are shown in Figure 6. It can be seen from the comparison that the point target by clustering, the computational complexity can be greatly reduced.

By comparing clustering and non-clustering, it can be seen that in large-scale problems, the ability of continuous search using ant colony algorithm search is weak, and the calculation time increases exponentially with the size of the problem, and the optimal solution yield value is also lower than the cluster group. Under the premise that the solution performance and calculation time are lower than the cluster group, the hierarchical algorithm based on task clustering can effectively solve the task planning problem of a large number of point targets, improve the efficiency of task planning, and save the calculation time.

### B. COMPARISON OF OPTIMAL PATH AND SHORTEST PATH

The hybrid optimization algorithm is used to solve the optimal path and the shortest path respectively under a certain energy condition, and the number of tasks completed is compared. Since the ant colony algorithm sets the parameters as shown in Table 1 in the above example. The shortest path only considers the distance between the center points of the cluster, while the optimal path considers the distance between the center points of the cluster and the number of tasks in the cluster, so as to analyze the total number of tasks completed under certain energy conditions. Since the hybrid optimization algorithm is particularly sensitive to parameters, different scale examples need to be configured with different parameters. The specific parameters of this experiment are shown in Table 2.

In the process of outer mission planning, in addition to considering the path between clusters, it is also necessary to consider the number of points between clusters, and reasonably consider the relationship between the two. In the case of ensuring optimal energy, the number of tasks completed is more.

In the past, the heuristic function factor of the shortest path frequently uses the reciprocal of the traditional distance, as shown in equation (8).

\[
\eta_{ij}(t) = \frac{1}{d_{ij}}
\]  

(8)

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**TABLE 1. Clustering target information.**

| Num | X-axis | Y-axis | The number of tasks in the cluster | Shortest path within the cluster |
|-----|--------|--------|----------------------------------|---------------------------------|
| 1   | 0      | 0      | 0                                | 0.0000                          |
| 2   | 16.5   | 3      | 5                                | 16.8535                         |
| 3   | -41    | 4.2    | 3                                | 10.2836                         |
| 4   | -6.5   | 9      | 19                               | 44.3572                         |
| 5   | -3     | -1.8   | 14                               | 41.6488                         |
| 6   | 20     | 10.2   | 12                               | 21.5142                         |
| 7   | -20    | -4.8   | 7                                | 17.6723                         |
| 8   | -26.5  | 10.2   | 4                                | 13.8633                         |
| 9   | 26.5   | 1.8    | 9                                | 25.1369                         |
| 10  | 30     | 11.4   | 12                               | 23.5504                         |
| 11  | 33.5   | -3.6   | 7                                | 18.1442                         |
| 12  | 8.5    | 9      | 13                               | 19.6112                         |
| 13  | -10    | -12.6  | 4                                | 8.3139                          |
| 14  | 18.5   | 5.4    | 7                                | 21.4995                         |
| 15  | 6.5    | -10.8  | 7                                | 15.1278                         |
| 16  | -33.5  | -4.8   | 6                                | 13.7002                         |
| 17  | -43    | -12    | 8                                | 23.9035                         |
| 18  | -13    | -6.6   | 4                                | 15.0308                         |
| 19  | -4     | -12    | 4                                | 8.7750                          |
| 20  | 13.5   | -7.8   | 3                                | 7.1391                          |
| 21  | 32     | -9.6   | 3                                | 9.6311                          |
| 22  | 40.5   | -2.4   | 3                                | 7.9660                          |
| 23  | 31.5   | 4.2    | 3                                | 8.1207                          |
| 24  | -33.5  | 12.6   | 5                                | 13.4713                         |
| 25  | -29    | 6      | 4                                | 15.2283                         |
| 26  | 39     | 13.2   | 19                               | 29.8466                         |
| 27  | 38.5   | 4.8    | 8                                | 26.0328                         |
| 28  | -36.5  | -9     | 4                                | 7.2501                          |
| 29  | -16.5  | 6.6    | 1                                | 0.0000                          |
| 30  | 23.5   | -11.4  | 1                                | 0.0000                          |
| 31  | -47.5  | -3     | 1                                | 0.0000                          |

---

**FIGURE 5. Maintenance path within the cluster set.**

**FIGURE 6. Comparison of simulation time between 200-point target clustering and no clustering.**
TABLE 2. Hybrid optimization algorithm parameter settings.

| Parameter                     | Number |
|-------------------------------|--------|
| Number of ants $m_a$          | 100    |
| Pheromone factor $\alpha$     | 1.3    |
| Heuristic factor $\beta$      | 4.2    |
| Pheromone intensity $Q$        | 10     |
| Pheromone volatile factor $\rho$ | 0.1   |
| Minimum pheromone Residual factor | 0.2   |
| Pheromone smoothing factor $\delta$ | 0.5   |
| Outer layer iterations        | 500    |
| Inner layer iterations        | 200    |
| Tabu table length             | 21     |
| Number of candidate solutions | 200    |
| Tabu times                    | 4      |

$d_{ij}$ is the distance between node $i$ and node $j$.

The heuristic function adopted by the optimal path is as shown in equation (9).

$$\eta_{ij}(t) = \frac{1}{\lambda_1 \cdot d_{ij} + \lambda_2 \cdot \text{ClusterNum}_j}$$  \hspace{1cm} (9)

Among them, $\lambda_1$ represents the weight of the distance between the center points of the cluster, and $\lambda_2$ represents the weight of the number of tasks in the cluster, $d_{ij}$ represents the distance between node $i$ and node $j$, and ClusterNum$_j$ represents the number of tasks in cluster node $j$. Solve the optimal path for space robot maintenance by setting the weight values $\lambda_1$ and $\lambda_2$ reasonably.

The total energy consumed by the space robot Consumption is expressed as

$$\text{Consumption} = \omega_1 \cdot \text{Num} + \omega_2 \cdot \text{Dist}_\text{Cluster}_\text{Out} + \omega_3 \cdot \text{Dist}_\text{Cluster}_\text{In}$$  \hspace{1cm} (10)

Among them, $\omega_1$, $\omega_2$ and $\omega_3$ are the corresponding energy consumption values, $\text{Num}$ represents the number of points within the cluster, $\text{Dist}_\text{Cluster}_\text{Out}$ represents the distance between the clusters, and $\text{Dist}_\text{Cluster}_\text{In}$ represents the distance within each cluster.

The energy of space robots is limited, so the number of tasks that can be completed under certain resources is mainly considered. The optimization function is

$$\text{Obj} = \sum_{i \in \text{allowed}} x_i$$  \hspace{1cm} (11)

Assuming that the total energy of the space robot is 5000, the energy consumed by the space robot to repair a fault point is 10, the energy consumed by the space robot to move 1m is 50, and the energy of the space robot’s robot arm moving 1m is 4. Based on the clustering comparison experiment, the initial space robot is fixed at the position of point $(0,0)$, calculate the number of solar cell arrays repaired by space robots under certain energy conditions. The experiment is repeated 30 times in consideration of the shortest path and the optimal path respectively to obtain the maintenance path, and the number of tasks completed is shown in Table 3.

The specific maintenance route of the space robot is shown in Figure 7. The starting point of the optimized path is the starting point of the space robot, namely node 1, and its shortest path and optimal path are shown in Figure 7 (a) and Figure 7 (b) respectively.

In space, resource constraints are one of the main factors affecting space robots, and it is necessary to maximize the benefits in limited resources. It can be clearly seen from Table 3 that under the condition of certain resources, the number of tasks completed by the optimal path is significantly better than the shortest path, and the number of tasks completed by the optimal path is 42% more than the number of tasks completed by the shortest path. However, in some cases,
TABLE 4. Comparison of different types of ant colony algorithms.

| Node | Algorithm  | Optimal solution | The number of iterations |
|------|------------|------------------|--------------------------|
| 30   | Basic ACO  | 185.5604         | 99                       |
| 30   | Adaptive ACO | 182.8316     | 458                      |
| 30   | Hybrid      | 181.0959        | 46                       |
| 50   | Basic ACO  | 349.3246        | 478                      |
| 50   | Adaptive ACO | 348.2486     | 223                      |
| 50   | Hybrid      | 337.8665        | 159                      |

FIGURE 8. Variations in the iteration step size of different algorithms over time: (a) 30 nodes; (b) 50 nodes.

By comparing the algorithms of different sizes and types in table 4, some conclusions can be drawn. The optimal solution of hybrid optimization algorithm is better than that of adaptive ant colony algorithm and basic ant colony algorithm. The simulation results show that the pheromone smoothing mechanism is introduced into the hybrid optimization algorithm to avoid the algorithm falling into local optimization to a certain extent, and the memory function of tabu search and contemp criteria are introduced into the hybrid optimization algorithm to make the algorithm accept inferior solutions to a certain extent and increase the global search capability of the algorithm. To sum up, the hybrid optimization algorithm is superior to other algorithms in optimization ability.

It can be seen from Figure 8 that the number of iterations of the optimal solution of the hybrid optimization algorithm under different iteration rounds is significantly better than that of the basic ant colony algorithm (Basic ACO) and the adaptive ant colony algorithm (Adaptive ACO). The reason is that the tabu search strategy makes the hybrid optimization algorithm get a better solution at the beginning of the search. As the scale continues to increase, the convergence of hybrid optimization algorithms is getting better and better.

V. CONCLUSION

The on-orbit maintenance mission planning problem of large-scale space solar power station is one of the hotspots in the space mission planning research. SSPS is an extremely complex space system, the modified clustering algorithm can plan the path globally, adjusting the number of clusters according to the requirements reasonably, thereby controlling the size of the cluster, assigning tasks to the space robot through layering, and then applying the optimization algorithm to calculate the optimal path of the maintenance point. The hybrid optimization algorithm proposed in this paper has a great improvement in convergence, which makes the path of optimization more accurate and can solve the optimal path of maintenance under certain constraints of resources. It is an effective solution to the problem of space maintenance mission planning.

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