Received March 22, 2021, accepted April 12, 2021, date of publication April 21, 2021, date of current version April 30, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3074710

The Collaborative Power Inspection Task Allocation Method of "Unmanned Aerial Vehicle and Operating Vehicle"

HUANG ZHENG[1], WANG HONGXING[1], ZHANG TIANPEI[1], AND YU BIN[2]
[1]Jiangsu Frontier Electric Technology Company Ltd., Nanjing 211102, China
[2]BDBC Laboratory, Beihang University, Beijing 100191, China
Corresponding author: Yu Bin (ybzhyb@163.com)

ABSTRACT In order to overcome the short battery life and poor long-distance maneuverability of Unmanned Aerial Vehicle (UAV) in power inspection operations, some provincial and municipal power companies promote a new mode of "UAV and operating vehicle (OV)" collaborative power inspection. This paper investigates into the actual problems in the cooperative inspection operations of the OV and multi-UAVs, and proposes a model of task allocation for the cooperative inspections of the OV and multi-UAVs, which includes four sub-problems: the division of a single operation circle, the location of parking spots, multi-UAVs task allocation, and the path planning of OV. The proposed model is solved by using improved K-means algorithm and genetic algorithm, and case analysis is carried out. The calculation results show that the model of task allocation for cooperative inspections proposed in this paper is practical and feasible, which can provide theoretical guidance for actual power inspections.

INDEX TERMS Operating vehicle, unmanned aerial vehicle, power inspection, task assignment.

I. INTRODUCTION

The power grid is an efficient and fast energy transmission channel and an optimized configuration platform. It is a key link in the sustainable development of energy and power and has a bearing on national energy security. With the rapid development of the national economy, the continuous growth of the people's daily electricity demand and the continuous advancement of the construction of the global energy Internet, the scale of long-distance and large-span overhead transmission lines has been continuously expanded, and the geographical environment of the line corridors has become increasingly complex [1]. It is indispensable to conduct regular inspections of transmission lines to grasp changes in line operating conditions and discover equipment defects and factors in time, which contributes to eliminating hidden dangers and preventing accidents [2].

Due to the problems of high labor intensity, difficult working conditions, and low labor efficiency [3], the traditional manual line inspection operation methods [4] can no longer fully meet the safe operation and maintenance requirements of modern ultra-high voltage (UHV) power grids. The practical experience of State Grid Corporation of China has indicated that, as a new type of power inspection method [5], Unmanned Aerial Vehicle (UAV) not only reduces the labor intensity of transmission line operation and maintenance personnel, but also improves the inspection quality, efficiency and benefit [6]. UAV inspection turns to be the main development direction of UHV grid transmission line operation and maintenance in the future.

However, there exists operation and acquisition process confusion resulting from manual operation of the drones for transmission line inspection. Besides, the drones suffer the disadvantages of poor long-distance maneuverability and short battery life [7]. In order to solve the above problems, some power companies launched a new type of power inspection operation mode of "UAV and operating vehicle (OV)". This operating mode consists of one OV and multiple drones. The OV is used as a transport carrier and replenishment station for drones. It transports drones over long distances and provides power supplies for drones. The integration of OV and UAV combines the advantages of both sides and enhances the professionalism and efficiency of power inspection work.

At present, the inspection process, OV path, and drone task allocation process still rely on the experience of inspectors [8]. Operating vehicles and drones' scheduling schemes

The associate editor coordinating the review of this manuscript and approving it for publication was Zhaojun Li.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

directly affect the efficiency of the power inspection. UAV and vehicle cooperation can significantly improve power detection efficiency [9], so how to achieve the scientific scheduling of vehicles and drones has high practical application value.

As far as we know, there are a few studies on this new inspection mode [10]. However, there are more researches on the application of vehicle path planning and UAV task allocation in other fields. The problem of UAV task allocation is essentially a combinatorial optimization problem. Commonly used UAV task allocation models can be listed as follows: Multiple Travelling Salesmen Problem (MTSP) [11]–[13], Vehicle Routing Problem (VRP) [14], Network Flow Optimization (NFO) [15], Mixed-Integer Linear Programming (MILP) [16], [17], Cooperative Multiple Task Assignment Problem (CMTAP) [18], [19]. The optimization algorithm can be used to solve the UAV task allocation problem [20], but since the UAV task allocation problem is an NP-Hard problem, the heuristic algorithm has a wider application range [21]–[26]. At present, a large number of researchers are studying truck-drone problems in the logistics transportation field [27]–[32]. Although these studies cannot directly provide theoretical guidance for this new inspection mode, they can provide reference for the research of this article.

The contribution of this paper can be summarized as follows:

In this paper, the task assignment problem of cooperative inspections between OV and multi-UAVs is divided into four sub-problems. Through the establishment of multi-UAVs task allocation model and OV path planning model, clustering algorithm and genetic algorithm are used to solve the problem. The tower coordinates of the area to be inspected are solved to obtain the driving path of the OV and the task set of each drone, which can provide theoretical guidance for actual power inspection work.

II. "UAV AND OV" COLLABORATIVE INSPECTION TASK ALLOCATION MODEL

The "UAV and OV" collaborative inspection problem can be described as: given that the relevant parameters of the drone and OV is deterministic, the solution is obtained including the driving path of the OV and task sequence for each UAV. The solution satisfies all constraints and makes it the shortest time to complete all inspection tasks in the operation area of the power company.

A. PROBLEM DESCRIPTION

The operation situation of the "UAV and OV" inspection mode is shown in Figure 1. As a transport carrier and replenishment station of the drones, the OV can carry the drone to maneuver in a wide range and provide electricity for the drones. The OV carries the drones to each parking spot, and releases the drones to complete the inspection task of all the towers within the operating radius of the parking spot. The drones return to the OV after completing the inspection task at a certain parking spot. Then the OV carries all drones to the next parking spot, and continues to complete the inspection of all the towers within the operating radius of the next parking spot. After all the towers in the operation area of the power company have been inspected, the OV will return to the power company.

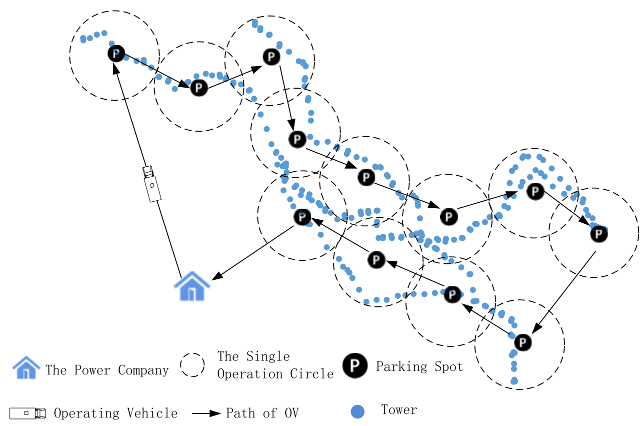

FIGURE 1. Schematic diagram of "UAV and OV" inspection.

B. MODEL ASSUMPTIONS

Based on the actual power inspection situation and the UAV power inspection operation constraints, in order to carry out quantitative research conveniently, the following reasonable assumptions are made for the construction of the OV and multi-UAVs collaborative inspection model:

(1) The drones carried on the OV are homogeneous, and each drone has the same flying speed;

(2) Since the precise inspection and shooting steps of power towers by drones have been standardized, the shooting steps of all types of power towers are similar. In order to facilitate calculation and analysis, it is assumed that all the power towers in the area to be inspected require the same inspection time. And the inspection time is much longer than the flying time of the drone between the target tower and the parking spot;

(3) The time for each drone to take off, land at the parking spot and replace the battery is negligible;

(4) Constrained by the current UAV endurance and safe return requirement, an UAV can only complete the inspection task of one tower in a single take-off and landing process. At this stage, due to the positioning accuracy, the landing parking spot must be the same as the take-off parking spot of the current flight;

(5) Due to the limitation of cost and actual situation, each power company is currently equipped with only one OV. A single OV is equipped with four homogeneous multi-rotor drones and multiple drone batteries, which can fully satisfy inspection needs for all UAVs.

C. MODEL CONSTRUCTION

In the problem of coordinated power inspection of OV and multi-UAVs, the total time to complete all the tower inspection tasks in the operation and maintenance area of the power company consists of two parts, the driving time of the OV and the inspection time of the drones. The driving time of the OV is determined by the driving path between the company and each parking spot, and the inspection time of the UAV is determined by the UAV task sequence in each parking spot.

Therefore, the task allocation problem of cooperative inspection tasks between OV and multi-UAVs needs to solve the following three sub-problems:

(1) The division of a single operation circle and the location of parking spots;

(2) The problem of multi-UAVs task allocation at each parking spot;

(3) Path planning of the OV.

The problem (1) uses the K-means clustering method to divide the operation and maintenance area of the power company into multiple single operation circles, and uses the center of gravity method to select the parking spot of each single operation circle. Questions (2) and (3) can be respectively established as a multi-UAV task allocation model and a vehicle path planning model.

1) LABEL AND PARAMETER DESCRIPTION

Model parameters and variables are shown in Table 1.

2) MULTI-UAV TASK ALLOCATION MODEL

The task allocation model of multi-UAVs at parking spot p is defined as follows:

$$\min \mathrm{T}'_{lp} = \max \left\{\mathrm{T}_{kp}\right\} \tag{1}$$

$$\sum_{k\in U} \mathrm{x}_{ki} = 1, \forall i \in D_{Tp} \tag{2}$$

$$\sum_{k\in U} \mathrm{y}_{kp} = m, p \in D_P \tag{3}$$

$$\sum_{i\in D_{Tp}} \mathrm{x}_{ki} \leq \left|S_p\right| - 1, \forall \mathrm{k} \in \mathrm{U}, \left|S_p\right| \geq 2 \tag{4}$$

$$\left(2 \cdot \mathrm{x}_{ki} \cdot d_{ip}\right) / \mathrm{v}_k + \mathrm{x}_{ki} \cdot C_i \leq t_k^{max}, \forall \mathrm{i} \in D_{Tp}, \forall k \in U \tag{5}$$

$$\mathrm{T}_{kp} = \left(2 \cdot \sum_{\mathrm{i}\in D_{Tp}} \mathrm{x}_{ki} \cdot d_{ip}\right) \Big/ \mathrm{v}_k + \sum_{\mathrm{i}\in D_{Tp}} \mathrm{x}_{ki} \cdot C_i \leq t_k^{max}, \forall k \in U \tag{6}$$

$$\mathrm{x}_{ki} \in \{0, 1\}, \forall k \in U, \forall i \in D_{Tp} \tag{7}$$

The objective function(1) minimizes the longest task time of UAV at parking spot p; formula (2) indicates each tower only inspected once by one UAV; formula (3) indicates the take-off times of all UAVs at parking spot p equal to the total number of all towers in the single operation circle p, that is, only one tower is inspected by a single UAV in a single take-off; formula (4) eliminates the constraints of the sub loop; formula (5) indicates the endurance constraint of UAV; formula (6) calculates the total task time of a single UAV at parking spot p; formula (7) is decision variable constraint.

TABLE 1. Model parameters and variables.

label	meaning
	Set
D_C	the set of power company location points
D_P	the set of parking spots of OV , $D_P = \{p_1, p_2, \ldots, p_n\}$
D_{Tp}	the set of tower points in single operation circle p, $D_{Tp} = \{D_{1p}, D_{2p}, \ldots, D_{mp}\}$
U	the set of UAV, $\mathrm{U} = \{\mathrm{U}_1, \mathrm{U}_2, \ldots \mathrm{U}_k\}$
OV	the set of OV, $\mathrm{OV} = \{\mathrm{OV}_1\}$
	Parameter
d_{ip}	the straight-line distance between tower i,$\mathrm{i} \in D_{Tp}$, and its corresponding parking spot p
d'_{pq}	the straight-line distance between the path points p, $\mathrm{p} \in D_P \cup D_C$, of the OV and the path points q, $\mathrm{q} \in D_P \cup D_C$
v_k	the average flight speed of UAV k, $\mathrm{k} \in \mathrm{U}$
v'_l	the average running speed of OV l, $\mathrm{l} \in \mathrm{OV}$
t_k^{max}	the maximum endurance time of single takeoff of UAV k, $\mathrm{k} \in \mathrm{U}$
T_{kp}	the total operation time of UAV k, $\mathrm{k} \in \mathrm{U}$, at parking spot p
T'_{lp}	the total operation time of OV l, $\mathrm{l} \in \mathrm{OV}$, at parking spot p
T'_l	the total time of OV l, $\mathrm{l} \in \mathrm{OV}$, to complete all inspection tasks in the operation and maintenance area
D'_l	the total driving distance of OV l, $\mathrm{l} \in \mathrm{OV}$
S_p	S_p is any subset of D_{Tp}, $S_p \subseteq D_{Tp}$
C_i	inspection time of UAV at tower i, $\mathrm{i} \in D_{Tp}$
y_{kp}	The number of the UAV k, $\mathrm{k} \in \mathrm{U}$, takeoffs at the parking spot p, $\mathrm{p} \in D_P$
	Variable
x_{ki}	1, if the UAV k, $\mathrm{k} \in \mathrm{U}$, visits the tower i, $\mathrm{i} \in D_{Tp}$; 0, otherwise
z_{lpq}	1, if the OV l, $\mathrm{l} \in \mathrm{OV}$ drives from the path point p, $\mathrm{p} \in D_P \cup D_C$, to the path point q, $\mathrm{q} \in D_P \cup D_C$; 0, otherwise
w_{lp}	1, if the OV l, $\mathrm{l} \in \mathrm{OV}$, accesses the path point p, $\mathrm{p} \in D_P \cup D_C$; 0, otherwise

3) PATH PLANNING MODEL OF OV

The path planning model of OV is defined as follows:

$$\min \mathrm{D}'_l = \sum_{\mathrm{p}\in D_P \cup D_C} \sum_{\mathrm{q}\in D_P \cup D_C} z_{lpq} \cdot d'_{pq} \tag{8}$$

$$\sum_{l\in OV} w_{lp} = 1, \forall \mathrm{p} \in D_P \tag{9}$$

$$\sum_{l\in OV} w_{lp} = 1, p = D_C \tag{10}$$
$$\sum_{p\in D_P} z_{lpq} = w_{lp}, q \in D_P, \forall l \in OV \tag{11}$$
$$\sum_{q\in D_P} z_{lpq} = w_{lp}, p \in D_P, \forall l \in OV \tag{12}$$
$$\min T_l^{'} = \sum_{p\in D_P\cup D_C} \sum_{q\in D_P\cup D_C} z_{lpq} \cdot \frac{d_{pq}^{'}}{v_l^{'}} + \sum_{p\in D_P} T_{lp}^{'} \tag{13}$$
$$z_{lpq} \in \{0, 1\}, \forall l \in OV, \ \forall p, q \in D_P \cup D_C \tag{14}$$
$$w_{lp} \in \{0, 1\}, \forall l \in OV, \ \forall p \in D_P \cup D_C \tag{15}$$

Formula (8) minimizes the total driving distance for the OV to complete all inspection tasks in the operation and maintenance area; formula (9) indicates that each parking spot is visited only once; formula (10) indicates that OV will eventually return to the power company after it leaves the power company; formula (11) and formula (12) indicate that each parking spot is visited only once; formula (13) indicates the total time for the OV to complete all inspection tasks in the operation and maintenance area; formula (14) and formula (15) are the decision variable constraints.

III. SOLUTION

A. SOLUTION PROCESS

For the task allocation problem of cooperative inspections between OV and multi-UAVs, the solution process is shown in Figure 2, which is divided into the following four steps:

(1) First, the operation and maintenance area of the power company is based on the administrative division of the government. The operation and maintenance area of a single power company is much larger than the maneuvering range of a single drone and the single parking spot operating range of the OV. The area is divided into multiple single operation circles based on the operating radius of the OV. Each single operation circle is the operating range of the OV for a single parking. This step can divide the operation and maintenance area of the power company into multiple single operation circles.

(2) Secondly, for each single operation circle, it is necessary to select a point in the circle as the parking spot. Since the single operation circle takes the working radius of the OV as its diameter, the straight-line distance from any point in the circle to the poles in the circle is less than the working radius of the OV. The OV can release the drones to visit all the towers to be inspected in the single operation circle.

(3) Thirdly, when the single operation circle and the parking spot of the operation circle are known, it is necessary to assign tasks of all the towers to be inspected in the single operation circle to multiple drones to minimize the total task time of drones in the circle. With the optimization goal of minimizing the total task time of a single operation circle, the optimal UAV task allocation plan under the parking spot is solved, and the total task time of the single operation circle is shortened.

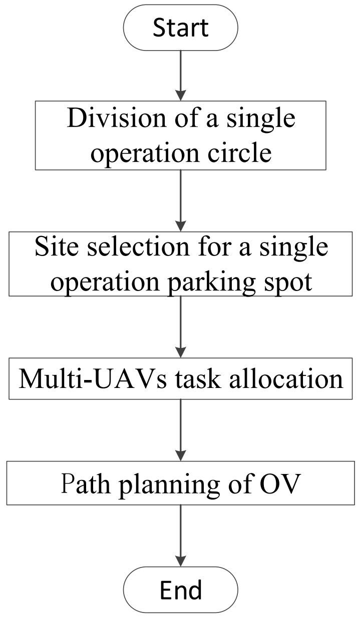

FIGURE 2. Task allocation solving process of the "UAV and OV" inspection mode.

(4) Finally, by optimizing the access sequence of each parking spot in the set, the shortest OV travel path is obtained to shorten the travel distance of the OV during non-patrol inspection; we can reduce the driving time of the OV and improve the inspection efficiency.

To sum up, the task allocation problem of the cooperative inspections of the OV and the multi-UAVs investigates into the problems of the actual power inspection. When there are only the coordinates of the towers of the area to be inspected and the relevant parameters of the drones and OV, through the research on the cooperative inspection task allocation method between OV and multi-UAVs, parking spot position, driving path of the OV, and the task set of the drones at each parking spot are solved. By minimizing the operation time, the total inspection time in the operation and maintenance area of the power company is shortened and the overall efficiency of the coordinated inspection of OV and UAVs is improved.

B. SOLVING ALGORITHM

As mentioned above, the task allocation problem of the cooperative inspections between OV and multi-UAVs is divided into four solving steps. The following is a detailed description of the solving algorithms involved in each step.

1) DIVISION OF A SINGLE OPERATION CIRCLE

In this paper, an improved K-means clustering algorithm is used to divide the operation and maintenance area of the power company based on the position distribution of the towers to be inspected. The traditional K-means clustering algorithm needs to determine k initial clustering center points, calculate the remaining data items of the sample set and the initial center points one by one, classify the data items

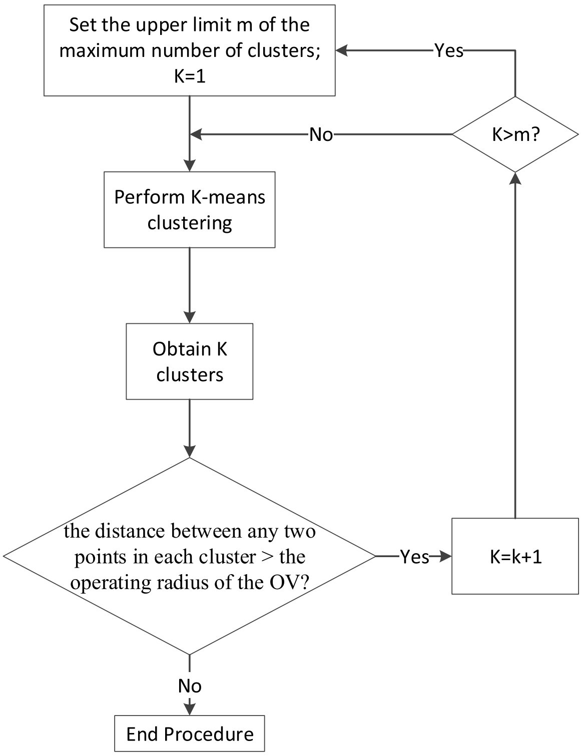

FIGURE 3. **The improved K-means algorithm flowchart.**

according to the distance and the whole sample set into k clusters, and find a new cluster center point for each cluster. Repeat the above steps until the cluster centers of the two adjacent calculations are no longer change and k cluster is obtained [33]. For the actual power inspection work, it is difficult to set a reasonable k value. Therefore, this paper improves the K-means clustering algorithm. The algorithm flow is shown in the Figure 3. Specifically, an upper limit m of the maximum number of clusters is initially set, k is calculated from 1, and clustering is performed. If the distance between any two points in each cluster exceeds the operating radius of the OV, then k +1. The above steps will be repeated until the distance between any two points in all clusters is less than the operating radius of the OV, so that the final result of the cluster is obtained. If the value of k reaches the upper limit m of the maximum number of clusters, there will be a situation where the distance between any two points in the cluster is larger than the operating radius of the OV, and then a larger m is set to re-cluster. The improved K-means clustering algorithm designed in this paper can solve the problem of difficulty in determining the number of initial clusters in actual power inspection work, divide the power work operation and maintenance area with the minimum number of clusters, and reduce the parking times of OV and improve the operation efficiency.

2) SITE SELECTION FOR A SINGLE ROUND PARKING SPOT

As mentioned above, this paper divides the operation and maintenance area of the power company into multiple single operation circles, and each single operation circle is a range that the OV needs to be inspected for a single parking. Combined with the actual power inspection situation, the OV needs to be parked once in each single operation circle, and the drones should be released at the parking spot to complete the inspection task of all towers within the single operating circle. Therefore, the parking spot of each single operation circle needs to be calculated as the parking position of the OV, that is, the take-off and landing positions of the UAV within the single operation circle. This paper uses the center of gravity method to solve the parking spot of a single operation circle. The center of gravity method is a simulation method and a common method in the location of logistics facilities. The demand points and resource points in the logistics system are regarded as the logistics system within a certain plane, where the demand and resource volume at each point are regarded as the weight of the object. The center of gravity of the logistics system is the best setting point for the logistics network. The calculation formula of the center of gravity method is shown in the formula 16 and formula 17. $\overline{X}$ and $\overline{Y}$ are the latitude and longitude of the parking spot to be determined respectively. X_i and Y_i are the latitude and longitude of each tower to be inspected in a single operation circle. w_i is the weight of demand, that is, the inspection time of each tower to be inspected, and h_i is the distance coefficient. Since the center of gravity method in this paper determines the take-off and landing point of the UAV, the distance between each tower to be inspected and the UAV can be expressed by a straight line distance, so h_i is taken as 1.

$$\overline{X} = \sum\nolimits_{i=1}^{n} h_i w_i X_i \Big/ \sum\nolimits_{i=1}^{n} h_i w_i \tag{16}$$

$$\overline{Y} = \sum\nolimits_{i=1}^{n} h_i w_i Y_i \Big/ \sum\nolimits_{i=1}^{n} h_i w_i \tag{17}$$

In this paper, the center of gravity method is used to select the location of the parking spot of a single operation circle, so that the location of the parking spot is at the physical center of the single operation circle, which can shorten the total flight distance of all drones in the single operation circle and reduce the total task time of all drones.

3) MULTI-UAVs TASK ALLOCATION

Through the above-mentioned single operation circle division and the determination of the location of parking spot, the power company operation and maintenance area are divided into multiple single operation circles. For each single operation circle, the UAVs are assigned tasks based on the parking spot of the single operation circle, and the task sequence of each UAV in each single operation circle is obtained by minimizing the longest UAV task time. Since the multi-UAVs task assignment problem is an NP-Hard problem, the heuristic algorithm is faster to solve and get a better solution. In this paper, combining the characteristics and practical application of the multi-UAVs task allocation model, a genetic algorithm with strong convergence and fast convergence speed is used to solve the multi-UAVs task allocation problem.

The steps of the genetic algorithm to solve the multi-UAVs task allocation problem are as follows:

Step 1: Parameter initialization. The initialization of the population size of the algorithm and the system parameters of the maximum number of iterations. The determination of the relevant information of the UAV, parking spot and towers.

Step 2: The generation of initial chromosomes. By using real number coding, the chromosomes are divided into n sub-segments according to the number n of drones, and each sub-segment chromosome is a task sequence of a drone. Connecting multiple sub-segments of chromosomes in a straight line is an individual chromosome, and each individual chromosome represents a task allocation plan for the parking spot.

Step 3: The calculation of the fitness of the initial population. The individual fitness value is the longest task time of the drones.

Step 4: Choice. The roulette method is used to select individuals in the population for crossover and mutation operations. The higher the fitness value is the lower the probability of being selected.

Step 5: Cross. 2-opt crossover method is used to generate offspring chromosomes from parent chromosomes.

Step 6: Variation. The mutation operation is performed by randomly selecting two pairs of non-adjacent gene positions to exchange gene values.

Step 7: Termination condition. The number of iterations or the amplitude of fitness change is terminated. According to the chromosome code, the task sequence of each drone is obtained.

The most dominant population obtained by the final calculation is the optimal multi-UAVs task allocation plan, and the total task time of the optimal task allocation plan is used as the inspection time of the parking spot.

In addition, since multiple drones operate simultaneously in the same single operation circle, conflicts and accidents may occur in the airspace. Different from the UAV obstacle avoidance method [34], [35], this paper designs a simple task check and adjustment method, as follows:

First, based on the solved optimal task allocation plan, the routes of all drones are drawn in space, and all routes are traversed to find the intersection between any two routes except for the parking point.

Secondly, if there is an intersection, calculate whether the time difference between the corresponding multiple drones to the intersection is within the preset danger threshold range, and if so, there is an airspace conflict.

Finally, for conflicting drones, we adjusted the order of the towers in the task allocation plan to avoid conflicts and do not change the total inspection time.

4) PATH PLANNING OF OV

The OV needs to start from the power company and return to the power company after visiting each parking spot in the task set. In order to shorten the driving distance of the OV and improve the work efficiency, it is necessary to plan the driving path of the OV to find the shortest driving path, and the total task time of the OV is equal to the sum of the inspection time plus the driving time. In this way, the minimum total task time for completing all the towers to be inspected in the operation and maintenance area of the power company can be solved.

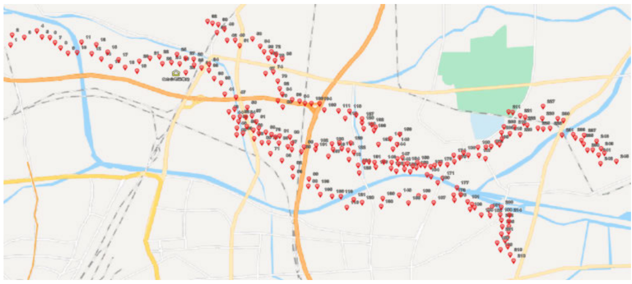

FIGURE 4. **Location map of power company and all towers.**

The path planning problem of the OV is a traditional VRP problem. This paper uses a genetic algorithm similar to 3.2.3 to solve it. The genetic algorithm is used to solve the driving path. The chromosome encoding in the genetic algorithm uses real number encoding method. The chromosome of each individual is the path sequence of the OV, and the individual fitness function is the length of the driving path. The selection operation of the genetic algorithm adopts the roulette method. The higher the fitness means the lower the probability of being selected. The crossover and mutation operations are the same as those in section III.B.3.

IV. CASE ANALYSIS

In order to verify the effectiveness of the proposed task allocation method for cooperative inspection model of OV and multi-UAVs, this article takes the inspection requirements of a power company as an example. Due to data privacy, all tower coordinates are added with a random number based on the actual latitude and longitude coordinates. This ensures that the overall position distribution of all towers is similar to the actual situation. The position distribution of the power company and all the towers after data preprocessing is shown in the Figure 4.

In particular, all distances in this example are real distances calculated using latitude and longitude coordinates.

In this example, the power company is equipped with an OV, carrying four drones. The average driving speed of the OV is 40km/h, the average flying speed of the drone is 60km/h, and the maximum endurance time of a single takeoff of the drone is 30min. All power towers in the operation and maintenance area are homogeneous, and the inspection time for each tower is 20min. Since the optimal communication distance of the UAV is 1.5km, the operating radius of the OV is also set as 1.5km. Given the position coordinates of all towers in the power company's operating area, the optimization goal is to minimize the total inspection time of all towers in the operation and maintenance area, and solve the position of all parking spots, task sequence for the drones at each parking spot and the driving path of the OV.

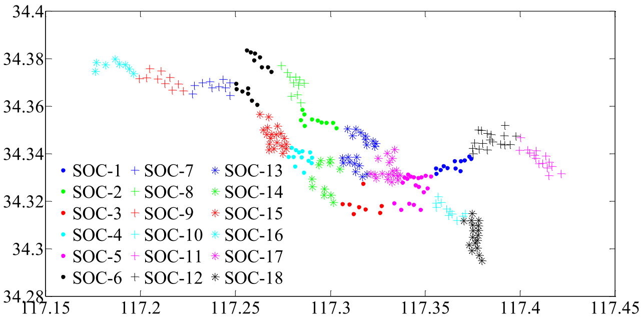

FIGURE 5. Diagram of distribution results of single operation circles.

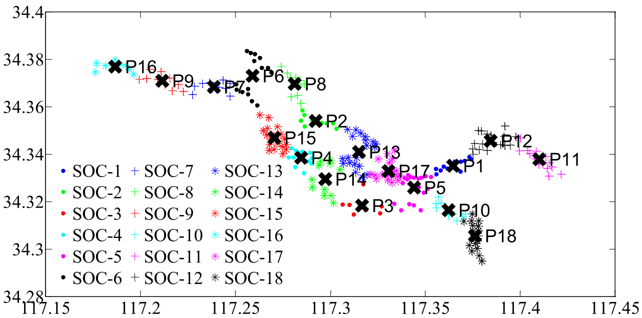

FIGURE 6. Location result map of parking spots.

In addition, according to the results of the preliminary experiment, we set the parameters of the genetic algorithm used to solve UAV task allocation and operating vehicle path planning as follows: population size is 80, crossover probability is 0.9, mutation probability is 0.01, and the number of iterations is 500.

A. CIRCLE DIVISION RESULTS OF A SINGLE OPERATION

In this paper, the improved K-means clustering algorithm is used to divide the entire power company operation and maintenance area, and the maximum number of clusters is set to 100. It is feasible when the radius of each single operation circle is smaller than the operating radius of the OV. The standard ensures that the distance between the subsequently selected parking spot and any point in the operating circle is less than the operating radius of the OV. The operation and maintenance area of the power company is clustered, and the clustering result is shown in the Figure 5. The entire operation and maintenance area is divided into 18 clusters, that is, 18 single operation circles.

B. THE RESULT OF A SINGLE OPERATION CIRCLE PARKING SPOT SELECTION

This paper uses the center of gravity method to select the location of the parking spot of each single operation circle to ensure that each parking spot is at the physical center of each single operation circle. The location results are shown in the Figure 6.

C. MULTI-UAVS TASK ASSIGNMENT RESULTS

Take the thirteenth single operation circle and its parking spot in Section IV.B as an example to introduce the results of multi-UAVs task allocation. Multi-UAVs task allocation takes minimizing the task time of the longest-consuming UAV as the optimization goal. The thirteenth single operation circle and its parking spot location distribution diagram is shown in Figure 7. The genetic algorithm is utilized to solve it, and the task assignment result of multiple UAVs is obtained, as shown in Figure 8. The task set of each UAV is shown in the Table 2. Since each drone only visits one base tower for a single take-off, each drone is independent of each take-off. So each tower in its task set can be visited in any order, which does not affect the drone's total task time of the parking spot. The total task time of each drone at the parking spot based on the task set is calculated, and the longest total task time of the drones is the total task time of the parking spot. Through calculation, the UAV that takes the longest time is U4, and its total task time is 108.6466 minutes, so the total task time of the single operation circle is 108.6466 minutes.

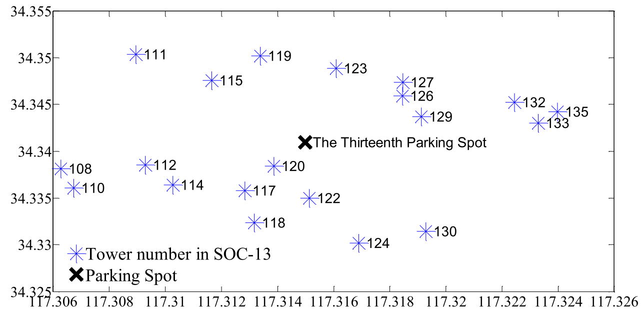

FIGURE 7. The thirteenth single operation circle and its parking spot distribution map.

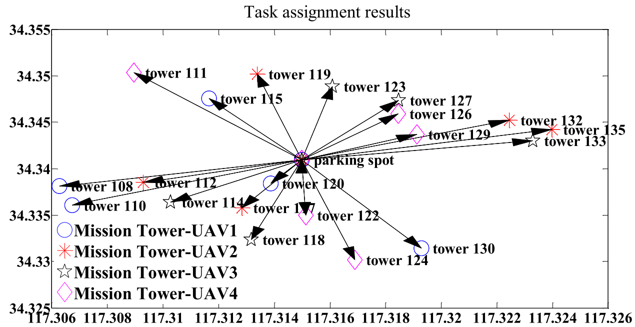

FIGURE 8. The task assignment result diagram of multiple UAVs.

TABLE 2. The task set of each UAV.

UAV umber	Task Set					Total Time (minute)
U1	120	115	108	130	110	108.6378
U2	135	132	119	112	117	108.6366
U3	123	127	118	133	114	108.6436
U4	111	124	122	126	129	108.6466

TABLE 3. The total task time of each single circle.

SOC number	Total Time (minute)	SOC number	Total Time (minute)
1	63.95	10	63.16
2	63.45	11	85.19
3	43.47	12	106.63
4	83.25	13	108.65
5	106.94	14	64.72
6	87.51	15	105.67
7	63.73	16	43.27
8	62.97	17	105.46
9	63.93	18	105.02

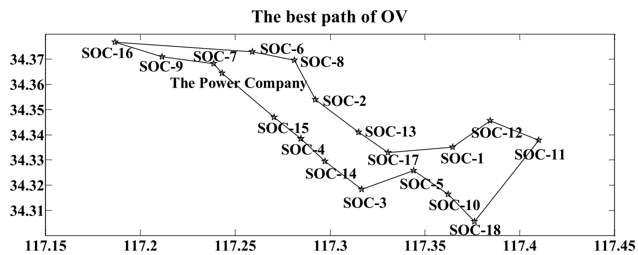

FIGURE 9. The shortest path solution of OV.

Calculate the total task time of each single operation circle in the same way. The calculation results are shown in the Table 3.

D. RESULTS OF THE PATH PLANNING OF THE OV

In order to shorten the total travel time, it is necessary to optimize the driving path of the OV. This paper uses genetic algorithm to plan the driving path of the working vehicle. The optimization goal is to minimize the total driving distance of the OV. The shortest path solution is shown in the Figure 9. The total task time of the OV includes the sum of the total task time of all single operation circles in the power work operation and maintenance area and the total travel time of the OV. The total time to complete all the tower inspection tasks in the operation and maintenance area of the power company is calculated as 1597.65 minutes.

It can be seen from the Figure 9 that the driving path of OV is: The Power Company-SOC7-SOC9-SOC16-SOC6-SOC8-SOC2- SOC13- SOC17-SOC1-SOC12-SOC11-SOC18-SOC 10-SOC5-SOC3-SOC14-SOC4-SOC15-The Power Company. For simplicity, use SOC to represent a single operation circle.

In summary, through the task distribution of OV and UAVs, the task allocation plan of UAVs at each parking spot and the driving path of the operating vehicle are obtained. It can be proved that the method proposed in this article is feasible.

V. CONCLUSION

This paper studies the task allocation of OV and drones in the "UAV and OV"

new power inspection mode, including single-operating circle division, single operating circle parking spot location, and multi-UAVs task allocation, and path planning of OV. After giving the description of the task allocation problem of the cooperative inspection of the OV and the UAV and its assumptions, the multi-UAVs task allocation model and the OV path planning model are established. The four sub-problems of task allocation for OV and UAVs are solved sequentially. First, the K-means algorithm is used to divide the operation and maintenance area into multiple single operation circles according to the position distribution of the towers in the operation and maintenance area. Secondly, the center of gravity method is used to locate parking spot of each single operation circle. Then, genetic algorithm is used to allocate multiple drone tasks for each single operation circle. Finally, the genetic algorithm is used for path planning of all parking spots in the task set of the OV. The total time of all tower inspection tasks in the operation area of the power company is obtained.

This article provides a calculation example designed based on the actual power company operation and maintenance area, and elaborates the solving steps of the task allocation model for cooperative inspections of OV and multi-UAVs proposed in this article. The results have shown the effectiveness and practical use of the method. In the future, the problem of task allocation for cooperative inspections between OV and multi-UAVs can also be studied in depth from the division of a single operating circle and the method of selecting parking spots.

REFERENCES

[1] Z. Liu, X. Wang, and Y. Liu, "Application of unmanned aerial vehicle hangar in transmission tower inspection considering the risk probabilities of steel towers," *IEEE Access*, vol. 7, pp. 159048–159057, 2019.

[2] A. Zormpas, K. Moirogiorgou, K. Kalaitzakis, G. A. Plokamakis, P. Partsinevelos, G. Giakos, and M. Zervakis, "Power transmission lines inspection using properly equipped unmanned aerial vehicle (UAV)," in *Proc. IEEE Int. Conf. Imag. Syst. Techn. (IST)*, Oct. 2018, pp. 391–395.

[3] L. Li, "The UAV intelligent inspection of transmission lines," in *Proc. Int. Conf. Adv. Mech. Eng. Ind. Informat.*, vol. 15, 2015, pp. 1542–1545.

[4] Y. Zhai, H. Zhao, M. Zhao, and S. Jiao, "Design of electric patrol UAVs based on a dual antenna system," *Energies*, vol. 11, no. 4, p. 866, Apr. 2018.

[5] Y. Zhang, X. Yuan, W. Li, and S. Chen, "Automatic power line inspection using UAV images," *Remote Sens.*, vol. 9, no. 8, p. 824, Aug. 2017.

[6] Z. Y. Liu, X. D. Zhao, H. C. Qi, Y. F. Li, G. B. Zhang, and T. Zhang, "Prospect of Power Inspection Using UAV Technology," *Commun. Comput. Inf. Sci.*, vol. 1228, pp. 151–159, Dec. 2020.

[7] Q. Gu, T. Fan, F. Pan, and C. Zhang, "A vehicle-UAV operation scheme for instant delivery," *Comput. Ind. Eng.*, vol. 149, Nov. 2020, Art. no. 106809.

[8] Z. Huang, X. Zhai, H. Wang, H. Zhou, H. Zhao, and M. Feng, "On the 3D track planning for electric power inspection based on the improved ant colony optimization and algorithm," *Math. Problems Eng.*, vol. 2020, pp. 1–11, Jun. 2020.

[9] J. Wang, G. Wang, X. Hu, H. Luo, and H. Xu, "Cooperative transmission tower inspection with a vehicle and a UAV in urban areas," *Energies*, vol. 13, no. 2, p. 326, Jan. 2020.
[10] M. Hu, W. Liu, J. Lu, R. Fu, K. Peng, X. Ma, and J. Liu, "On the joint design of routing and scheduling for vehicle-assisted multi-UAV inspection," *Future Gener. Comput. Syst.*, vol. 94, pp. 214–223, May 2019.
[11] P. Vincent and I. Rubin, "A framework and analysis for cooperative search using UAV swarms," in *Proc. ACM Symp. Appl. Comput.*, Nicosia, Cyprus, 2004, p. 5.
[12] N. Ozalp, U. Ayan, and E. Oztop, "Cooperative multi-task assignment for heterogonous UAVs," in *Proc. ICAR*, 2015, pp. 599–604.
[13] Y. Zehua, "MTSP UAV detection problem based on ant algorithm," in *Proc. 17th Int. Symp. Distrib. Comput. Appl. Bus. Eng. Sci. (DCABES)*, Oct. 2018, pp. 265–267.
[14] K. P. O'Rourke, W. B. Carlton, T. G. Bailey, and R. R. Hill, "Dynamic routing of unmanned aerial vehicles using reactive tabu search," *Mil. Oper. Res.*, vol. 6, no. 1, pp. 5–30, Dec. 2001.
[15] J. Xia, K. Wang, and S. Wang, "Drone scheduling to monitor vessels in emission control areas," *Transp. Res. B, Methodol.*, vol. 119, pp. 174–196, Jan. 2019.
[16] Y. Li, X. Yuan, J. Zhu, H. Huang, and M. Wu, "Multiobjective scheduling of logistics UAVs based on variable neighborhood search," *Appl. Sci.*, vol. 10, no. 10, p. 3575, May 2020.
[17] W. Stecz and K. Gromada, "UAV mission planning with SAR application," *Sensors*, vol. 20, no. 4, p. 1080, Feb. 2020.
[18] F. Ye, J. Chen, Y. Tian, and T. Jiang, "Cooperative task assignment of a heterogeneous multi-UAV system using an adaptive genetic algorithm," *Electronics*, vol. 9, no. 4, p. 687, Apr. 2020.
[19] F. Ye, J. Chen, Y. Tian, and T. Jiang, "Cooperative multiple task assignment of heterogeneous UAVs using a modified genetic algorithm with multi-type-gene chromosome encoding strategy," *J. Intell. Robot. Syst.*, vol. 100, no. 2, pp. 615–627, Nov. 2020.
[20] S. Poikonen, B. Golden, and E. A. Wasil, "A branch-and-bound approach to the traveling salesman problem with a drone," *INFORMS J. Comput.*, vol. 31, no. 2, pp. 335–346, Apr. 2019.
[21] F. Pan, X. Hu, R. Eberhart, and Y. Chen, "A new UAV assignment model based on PSO," in *Proc. IEEE Swarm Intell. Symp.*, Sep. 2008, p. 9.
[22] G. Na, Q. Zhi-hong, and L. Xiang-jun, "On modeling and discrete particle swarm optimization for task assignment of cooperating UAVs," in *Proc. Chin. Control Decis. Conf. (CCDC)*, May 2011, p. 1044.
[23] L. Lin, S. Qibo, W. Shangguang, and Y. Fangchun, "Research on PSO based multiple UAVs real-time task assignment," in *Proc. 25th Chin. Control Decis. Conf. (CCDC)*, May 2013, pp. 1530–1536.
[24] L. Zhong, Q. Luo, D. Wen, S.-D. Qiao, J.-M. Shi, and W.-M. Zhang, "A task assignment algorithm for multiple aerial vehicles to attack targets with dynamic values," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 236–248, Mar. 2013.
[25] T. Shima, S. J. Rasmussen, A. G. Sparks, and K. M. Passino, "Multiple task assignments for cooperating uninhabited aerial vehicles using genetic algorithms," *Comput. Oper. Res.*, vol. 33, no. 11, pp. 3252–3269, Nov. 2006.
[26] J. Senthilnath, S. N. Omkar, V. Mani, and A. R. Katti, "Cooperative communication of UAV to perform multi-task using nature inspired techniques," in *Proc. IEEE Symp. Comput. Intell. Secur. Defense Appl. (CISDA)*, Apr. 2013, pp. 45–50.
[27] C. C. Murray and A. G. Chu, "The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery," *Transp. Res. C, Emerg. Technol.*, vol. 54, pp. 86–109, May 2015.
[28] Y. S. Chang and H. J. Lee, "Optimal delivery routing with wider drone-delivery areas along a shorter truck-route," *Expert Syst. Appl.*, vol. 104, pp. 307–317, Aug. 2018.
[29] Z. Wang and J.-B. Sheu, "Vehicle routing problem with drones," *Transp. Res. B, Methodol.*, vol. 122, pp. 350–364, Apr. 2019.
[30] D. Wang, P. Hu, J. Du, P. Zhou, T. Deng, and M. Hu, "Routing and scheduling for hybrid truck-drone collaborative parcel delivery with independent and truck-carried drones," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10483–10495, Dec. 2019.
[31] P. Kitjacharoenchai, B.-C. Min, and S. Lee, "Two echelon vehicle routing problem with drones in last mile delivery," *Int. J. Prod. Econ.*, vol. 225, Jul. 2020, Art. no. 107598.
[32] J. Liu, Z. Guan, and X. Xie, "Truck and drone in tandem route scheduling under sparse demand distribution," in *Proc. 8th Int. Conf. Logistics, Informat. Service Sci. (LISS)*, Aug. 2018, p. 6.
[33] K. Yadav, S. Gupta, N. Gupta, S. L. Gupta, and G. Khandelwal, "Hybridization of K-means clustering using different distance function to find the distance among dataset," in *Inf. Commun. Technol. Intell. Syst.*, vol. 1, pp. 305–314, Oct. 2014.
[34] J. Tang, F. Zhu, and M. A. Piera, "A causal encounter model of traffic collision avoidance system operations for safety assessment and advisory optimization in high-density airspace," *Transp. Res. C, Emerg. Technol.*, vol. 96, pp. 347–365, Nov. 2018.
[35] J. Sun, J. Tang, and S. Lao, "Collision avoidance for cooperative UAVs with optimized artificial potential field algorithm," *IEEE Access*, vol. 5, pp. 18382–18390, 2017.

HUANG ZHENG is currently an Engineer with Jiangsu Frontier Electric Technology Company Ltd. His research interest includes UAV intelligent inspection technology.

WANG HONGXING is currently a Senior Engineer (professor level) with Jiangsu Frontier Electric Technology Company Ltd. His research interest includes UAV smart inspection technology.

ZHANG TIANPEI is currently an Engineer with Jiangsu Frontier Electric Technology Company Ltd. His research interest includes UAV intelligent inspection technology.

YU BIN is currently a Professor with BDBC, Beihang University. His research interests include the development and application of innovative models and ITS tools, like partway deadheading strategy, stop-skipping strategy, and bus travel-time prediction, for urban planning and transportation.