A Pesticide Spraying Mission Assignment Performed by Multi-Quadcopters and Its Simulation Platform Establishment*

Luo Yao, Yan Jiang, Zhao Zhiyao, Yang Shuaishuai and Quan Quan

***Abstract*—This paper proposes a new mission assignment scheme aimed at the farmland spraying problem by using the plant-protection-quadcopters. A mathematical model of the mission assignment problem is established by simplifying some minor factors of the optimization problem and a Sequential Quadratic Programming (SQP) method is used to obtain the optimal solution. Then, a simulation platform is established and a series of simulations are carried out to verify the reasonability and correctness of this mission assignment scheme.**

I. INTRODUCTION

Quadcopters [1], [2] are well-suited to a wide range of mission scenarios, such as search and rescue [3], [4], package delivery [5], border patrol [6], military surveillance [5], [7] and agricultural production [8]. For agricultural production, the plant-protection-quadcopters has been more and more widely used because of the shortage of rural labor force and the demand for high efficiency. With advancements in electronics and airframes, nowadays, the development direction of plant protection should be large-scale and high-efficiency with multi-aircrafts [9], [10]. Since the reform and opening up, Chinese government has released "Agriculture, Rural areas and Farmers" as the No. 1 Central Document for 18 times to solve it. In particular, since 2014, the "agricultural modernization" is written into the title of the No. 1 Central Document for three consecutive years. These documents indicate that there is an urgent need to push forward the building of "new socialist countryside", accelerate the transformation of the development mode of agriculture, accelerate agricultural modernization, and deepen rural reforms comprehensively. In recent years, many specific favorable policies related to civil aviation industry and plant protection have been announced by the Ministry of Agriculture of China, Civil Aviation Administration of China and the State Council. These policies indicate that civil aviation industry is an important strategic industry for the social and economic development of China and development of quadcopters for prevention and control of pests and diseases in some appropriate region deserves to be encouraged.

In civil aviation industry and plant protection field, a problem that has attracted particular attention is how to cover and traverse an agricultural region. Currently, there have been a lot of research on the coverage traversal problem in the field of both academic and engineering. Reference [11] proposes a cooperative coverage algorithm aimed at the collaborative search of an unknown grid environment by using multiple mobile robots. The collaborative search tasks may be mine detection, floor cleaning, and others are essentially coverage tasks, in which a robot must pass a sensor or effector over every point in its environment and a single robot with only intrinsic contact sensing can cover any finite rectilinear environment. This algorithm is performed by incrementally constructing a cellular decomposition of the environment (C) and using only the structure of C to determine the coverage path. Reference [12] uses real-time heuristic search methods to implement ant robots and presents a simulation study with several real-time heuristic search methods to study their properties for terrain coverage. Thus, by leaving markings in the terrain, coordinating teams of simple agents can implement mobile coverage of the terrain even if they do not communicate with each other except via the markings, do not have any kind of memory, do not know the terrain, cannot maintain maps of the terrain, nor plan complete paths. In the aspect of research on multi Unmanned Aerial Vehicles (UAVs), reference [13] proposes a method which begins with an arbitrary number of items of interest (targets) randomly distributed over a given geographic area and the definition of a launch/recovery point for the UAVs. The combinatorial optimization problem that finds the shortest path connecting each target on an idealized surveillance mission is then solved using the method of simulated annealing. Reference [14] considers that the area coverage should involve two stages - area decomposition into cells and path planning inside the cells and propose area decomposition using sweeping method and develop a novel method of generating lanes inside the cells such that the number of lanes is optimal and area can be covered considering persistence requirements into account. Then in the aspect of research on coverage flight path planning in a convex polygon area, reference [15] proves that the turning motion is less efficient compared to the flat flying theoretically from the viewpoints of energy, route length and duration. A high performance vertex-edge algorithm to obtain the width of a convex polygon is given based on the theorem which proves that only vertex-edge pairs need to be considered in the computation of the width. If a UAV flies along the direction of parallel lines of support with the obtaining of width, the coverage path can get the least number of turns.

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In practical engineering, three main plant-protection-quadcopters production companies in China are DJI, ZEROTECH and XAIRCRAFT, respectively. Figs.1-3 show the latest plant-protection-quadcopters produced by the three companies during the last two years which all have their own breakthroughs and advantages. The "MG-1" plant-protection-quadcopter produced by DJI extends the battery life up to more than 3 times. Meanwhile, the amount of work per hour can reach 40 to 60 acres and the operating efficiency is 40 times more than that by labour [16]. The "Protector-Z10" plant-protection-quadcopter produced by ZEROTECH has a tailored APP for agricultural applications and route recall capacity aimed at the route planning of irregular farmland [17]. The "P20" plant-protection-quadcopter produced by XAIRCRAFT uses an intelligent spraying system which can adjust spray flow intelligently based on the ground station instructions and weather information from the automatic weather station [18].

Fig. 1 "MG-1" produced by DJI

Fig. 2 "Protector-Z10" produced by ZEROTECH

Fig. 3 "P20" produced by XAIRCRAFT

The research of algorithm in theory is mainly for complex region, however, the region we concern in this research are regular, such as a rectangular region. Thus, all the methods in references [11]-[15] need to be simplified. The problem we study is a practical engineering problem of which the purpose is to save time, meanwhile, the situation of low battery capacity should be considered. Thus, this paper proposes a new mission assignment scheme aimed at the farmland spraying problem by using the plant-protection-quadcopters. A mathematical model of the mission assignment problem is firstly established. Then, the optimal solution is obtained by using a SQP method. For clarification, a simulation platform is established and a series of simulations are carried out to verify the reasonability and correctness of this mission assignment scheme.

The rest of the paper is as follows. Section II formulates the farmland spraying problem. In Section III, a mathematical model of the mission assignment problem is established and the optimization method is proposed. The simulation platform establishment and the results analysis are given in Section IV. Section V presents the conclusion and possible future research.

II. PROBLEM FORMULATION

The background of the research in this paper is a pesticide spraying mission performed by multi-quadcopters. Fig.1 presents a schematic diagram of the mission. The length and width of the rectangular farmland are w_r and h_r, respectively; the point O is the origin; the point $Base$ is the place that quadcopters take off. As the farmland is rectangular and the quadcopters can spray pesticides covering the farmland with a certain width w_0, the moving paths of the quadcopters can be depicted by the dotted lines. In order to make the quadcopters work in order, we make the following principles:

(1) Quadcopters can move in the 3-dimensional-space.

(2) The number of the quadcopters is greater than 1 and is arbitrary.

(3) There are four working modes of the quadcopters, including spray, Return To Base (RTB), Return To Work (RTW), charge. Note that quadcopters only spray pesticides during the "spray" mode.

(4) When the battery capacity of a quadcopter is low, the quadcopter will quickly return to base to charge and return to work after fully charging the batteries.

(5) The same region of the farmland is not permitted to be repeatedly sprayed by different quadcopters.

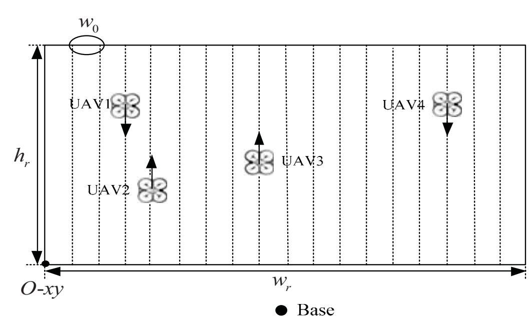

Fig. 4 A schematic diagram of the mission

Note that each dotted line in the Fig.1 is a unit task. Thus, the total number of moving paths satisfies $n = w_r / w_0$. All n tasks should be assigned to m quadcopters before the quadcopters starting to work, and the mission assignment scheme is to divide the rectangular farmland into m blocks and distributed to the m quadcopters.

In our research, on the premise of finishing the whole mission, how to reduce the mission time is the main problem this paper concerned. Let $T_{q,k}$ be total time to complete the task of the kth quadcopter. Then, the problem can be written as

$$\min(\max_k T_{q,k}) \ .$$

Obviously, different mission assignment scheme may result in different mission time. Thus, the problem of our research is transformed into the optimization problem of mission assignment scheme.

III. Establishment of the Mathematical Model and the Optimization Method

A. Establishment of the mathematical model

Before we establish the mathematical model, some useful parameters are defined as shown in TABLE Ⅰ.

TABLE I. Model parameters

Symbol	***Description***
n_k	Number of tasks assigned to the kth quadcopter
$n_{q,k}$	Charging times of the kth quadcopter
T_{charge}	Charging time of the kth quadcopter
d_k	Round-trip distance for charging of the kth quadcopter
V_q	Speed of the quadcopters
T_b	Flight time of the quadcopters after fully charging

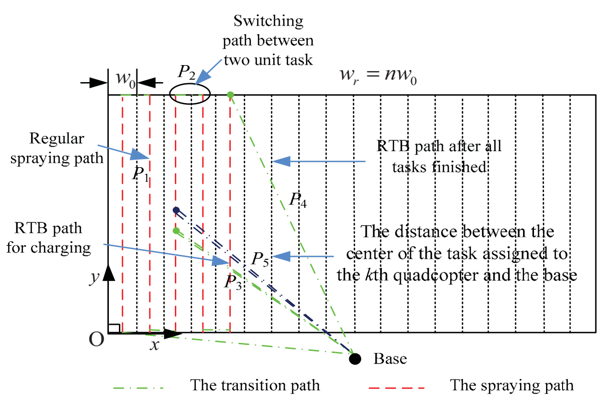

Fig. 5 Flight routes of quadcopters

As shown in Fig.2, the whole paths that a quadcopter moves are depicted. There are four kinds of paths, including regular spraying path p_1 (each p_1 equals to h_r), switching path between two unit tasks p_2 (each p_2 equals to w_0), RTB path for charging p_3 (equals to RTW path), RTB path after all tasks finished p_4.

For preciseness, some assumptions are made first.

Assumption 1. The distance d_k is viewed as constant for the quadcopters flying back and forth between the base and the farmland.

Remark 1. As the quadcopter position is different each time the kth quadcopter return to charge, the value of p_3 is different for each time, too. Meanwhile, different mission assignment scheme will make n_k have different values, and the value of p_4 is also different. Thus, in order to simplify the model, it is considered that the value of p_3 and p_4 are approximately the distance between the center of the tasks assigned to the kth quadcopter and the base p_5.

Assumption 2. The speed V_q is viewed as constant whenever the quadcopters are flying.

Remark 2. *Assumption 2* confines that the quadcopter flies with a same speed under different working modes. This assumption is without loss of generality.

Assumption 3. Battery capacity and charge time is identical for all quadcopters.

Remark 3. All the quadcopters are in a same type, meanwhile, the performances of batteries equipped on the quadcopters are similar. By ignoring the subtle difference between charge and discharge among individuals, we can consider that the battery capacity and charge time is identical for all quadcopters.

Based on these assumptions, a mathematical model of the mission assignment problem is established as follows:

$$\min_{n_k\in\mathbb{Z}_+, n_{q,k}\in\mathbb{Z}_+} \max_k T_{q,k} \ \cdot \tag{1}$$

s.t.

$$T_{q,k} = \frac{n_k h_r + w_0(n_k-1)+2(n_{q,k}+1)d_k}{V_q} + n_{q,k}T_{\text{Charge}} \ \cdot \tag{2}$$

$$n_k h_r + w_0(n_k-1)+2(n_{q,k}+1)d_k \le (n_{q,k}+1)V_qT_b \ \cdot \tag{3}$$

$$n_k h_r + w_0(n_k-1)+2(n_{q,k}+1)d_k > n_{q,k}V_qT_b \ \cdot \tag{4}$$

$$d_k = \sqrt{w_0^{\,2}(\bar{n}_{k_0}+n_k/2-n/2)^2+(h_r/2)^2} \ \cdot \tag{5}$$

$$\bar{n}_{k_0} = \sum_{i=1}^{k-1} n_i \ \cdot \tag{6}$$

$$\sum_{k=1}^{m} n_k = n \ \cdot \ \cdot \tag{7}$$

- Equation (1) is the optimization goal, which is to minimize the maximum working time of the quadcopters. It guarantees that all quadcopters have to complete the spraying mission and RTB at about the same time.
- If the number of tasks assigned to the kth quadcopter and charging times of the kth quadcopter are n_k and $n_{q,k}$, then the total p_1, p_2, distance of flying back and forth between the base and the farmland, flight routes, charging time and each sustainable flight length after fully charging of the kth quadcopter are $n_k h_r$, $w_0(n_k-1)$, $2(n_{q,k}+1)d_k$, $n_k h_r + w_0(n_k-1)+2(n_{q,k}+1)d_k$, $n_{q,k}T_{\text{Charge}}$ and V_qT_b, respectively.
- Constraint (2) represents the time for the quadcopters to complete their assigned tasks, which equals to the value that the flight routes of the quadcopters divided by the speed of the

quadcopters, and then plus the total charging time of the quadcopters.

- Constraints (3) and (4) represent the length of the flight routes of the quadcopters should be less than $(n_{q,k}+1)$ times the sustainable flight length after fully charging but more than $n_{q,k}$ times the sustainable flight length after fully charging, because the quadcopters are full of electricity at the very beginning.
- Constraint (5) represents the approximate distance of flying back and forth between the base and the farmland of the quadcopters, and the definition of $\overline{n}_{k_0}$ which presents the sum of tasks assigned to the first $(k-1)$ quadcopters is given in the constraint (6).
- Constraint (7) represents the sum of the number of the tasks assigned to m quadcopters is n.

B. Optimization Method

SQP has arguably become the most successful method for solving nonlinearly constrained optimization problems, since it shows its advantages when solving problems with significant nonlinearities in the constraints by solving quadratic sub problems [19], [20].

For clarify, we simplify equations (1)-(7) as follows:

$$\min f(\mathbf{x}) \tag{8}$$

$$\mathbf{G}_i = 0 \quad i = 1,\ \cdots,\ m_g \tag{9}$$

$$\mathbf{G}_i \le 0 \quad i = m_g + 1,\ \cdots,\ 6m \tag{10}$$

where $\mathbf{x} = [\mathbf{T}_q^{\mathrm{T}}, \mathbf{d}^{\mathrm{T}}, \mathbf{n}^{\mathrm{T}}, \mathbf{n}_q^{\mathrm{T}}]$ is the parameter vector; $\mathbf{T}_q = [T_{q,1},\ \cdots,\ T_{q,\mathrm{m}}]^{\mathrm{T}}$; $\mathbf{d}^{\mathrm{T}} = [d_1,\ \cdots,\ d_m]^{\mathrm{T}}$; $\mathbf{n}^{\mathrm{T}} = [n_1, \cdots,\ n_m]^{\mathrm{T}}$; $\mathbf{n}_q^{\mathrm{T}} = [n_{q,1},\ \cdots,\ n_{q,\mathrm{m}}]^{\mathrm{T}}$. The function $f(\mathbf{x})$ is the objective function, which can be obtained by simplifying equation (1). The vector $\mathbf{G}_{\mathbf{x}} = [g_1(\mathbf{x}), g_2(\mathbf{x}),\ \cdots,\ g_m(\mathbf{x})]$ is the functional vector, and m_g is the boundary value of the equality and inequality constraints. Constraints (9) and (10) represent the equality constraints and inequality constraints, respectively. Both $f(\mathbf{x})$ and $g(\mathbf{x})$ can be nonlinear functions.

Using the SQP method to solve the optimization problem in this paper mainly has the following four steps.

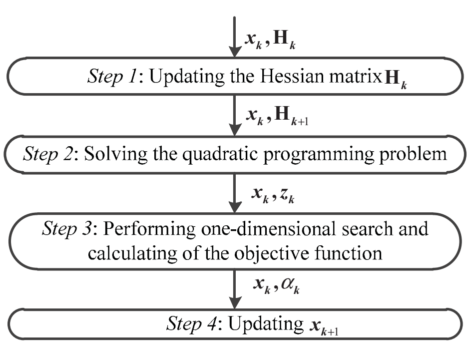

Fig. 6 Procedures of using the SQP method to solve the optimization problem

Note that $\mathbf{H}_k$ is the Hessian matrix of the Lagrange function and the initial $\mathbf{x}_0$ and $\mathbf{H}_0$ are arbitrary. The vector $\mathbf{z}_k$ is the full variable search direction, which presents a vector of $\mathbf{x}_k$ to $\mathbf{x}_{k+1}$. The parameter α_k presents a scalar step parameter which can be obtained by the appropriate linear search procedure. The vector $\mathbf{x}_{k+1}$ can be generated by setting $\mathbf{x}_{k+1} = \mathbf{x}_k + \alpha_k \mathbf{z}_k$ in the fourth step. A sequence of $\mathbf{x}_k$ can be generated by repeating the above four steps, and the local convergence properties of the SQP approach will be well understood when the optimum solution $(\mathbf{x}^*, \lambda^*)$ satisfies the second-order sufficiency conditions. If the starting point $\mathbf{x}_0$ is sufficiently close to $\mathbf{x}^*$, and the Lagrange multiplier estimates $\{\lambda_{\mathrm{k}}\}$ remain sufficiently close to λ^*, then the sequence converges to $\mathbf{x}^*$ which is the result of the optimization we want at a second-order rate.

IV. Simulation Platform Establishment and Results Analysis

A. Simulation Platform Establishment

In order to verify the reasonability and correctness of the optimal mission assignment scheme, a simulation platform is established using Matlab and a series of simulations are carried out. This simulation platform mainly includes four modules: parameter initialization, mission assignment, quadcopter control and plotting. Fig.3 is a block diagram showing how this simulation platform works. As shown in Fig.3, the values of m, h_r, w_r and w_0 are entered by the user, but other parameters such as the base, the current point, the current velocity, the destination point, the last point, the way point, the current way point, the maximum electric quantity, the charging rate, the consuming rate, the control parameter, the control precision, the control model and the quadcopter states are initialized by the parameter initialization module. The mission assignment module implements the optimal mission assignment scheme, the way point generation and the path planning on the basis of known parameters. The quadcopter control module implements the cooperative control of the quadcopters, the quadcopter attitude control and the quadcopter state determination. The plotting module implements moving path plotting in the "Mission display" area in Fig.3 based on the mission assignment scheme and the generated way point from the mission assignment module.

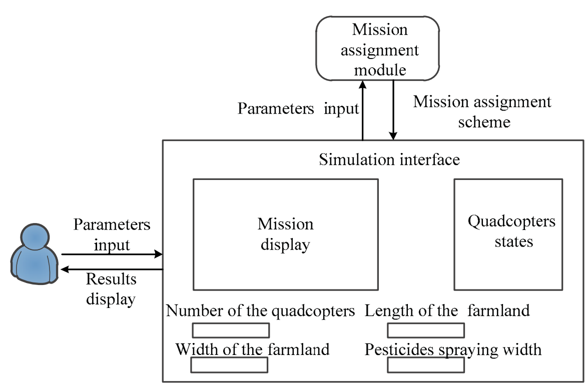

Fig. 7 A block diagram of the simulation platform

B. Results Analysis

The values of m, h_r, w_r and w_0 are given as 3, 60 meters, 300 meters and 10 meters, respectively, and so n is 30. In order to verify the reasonability and correctness of the optimal mission assignment scheme, two kinds of simulations have been carried out. One is to divide all tasks equally without optimization, and the other is to use the optimal mission assignment scheme to assign the tasks. Then, the time for each quadcopter to complete its mission is recorded. Fig.4 is the path diagrams showing the time for the first quadcopter to complete its mission when the tasks are divided equally without optimization, and Fig.5 is the path diagrams showing the time for the first quadcopter to complete its mission when use the optimal mission assignment scheme to assign the tasks.

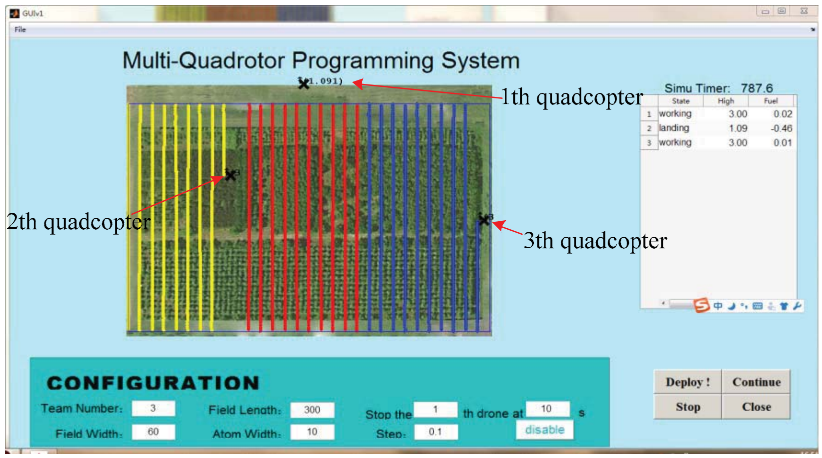

Fig. 8 The time for the first quadcopter to complete its mission when the tasks are divided equally

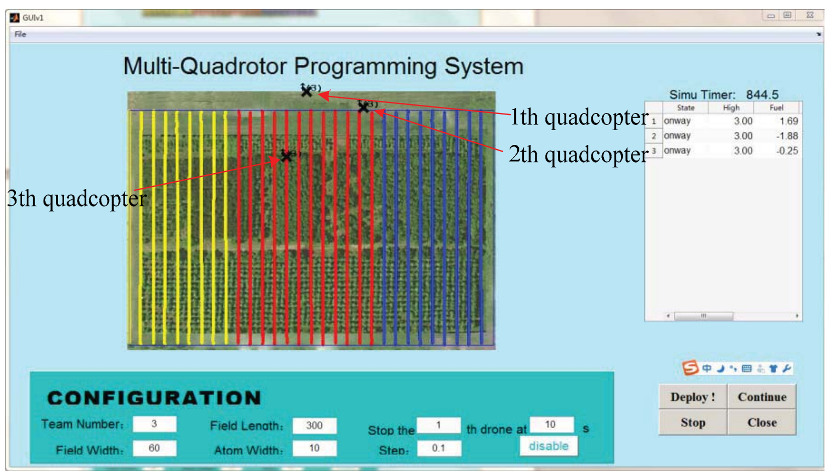

Fig. 5 The time for the first quadcopter to complete its mission when the optimal mission assignment method is used to assign the tasks

By comparing the above simulation path diagrams, it is known that the total time to complete the spraying task is different. When the sub tasks are divided equally, the number of sub tasks assigned to each quadcopter is 10 and the time for three quadcopters to complete its mission are 787.6, 956.6 and 985 simulation time intervals, respectively. When use the optimal mission assignment scheme is used to assign the tasks, the number of sub tasks assigned to three quadcopter are 9, 12 and 9, and the time for three quadcopters to complete its mission are 844.5, 855.6 and 872.6 simulation time intervals, respectively. From the above comparison results, we can know that the mission execution will be more efficient and the mission time of each quadcopter will be close to each other by using the optimal mission assignment scheme.

In order to make the simulation results more persuasive, more simulations are carried out, including 1) the same number of the quadcopters with the different size of the farmland, and 2) the different number of the quadcopters with the different size of the farmland. The results of the simulations are shown in TABLEs Ⅱ & Ⅲ. The parameter s_1 is the average allocation scheme; s_2 is the optimal mission assignment scheme; t_1 is the completion time of the average allocation scheme; t_2 is the completion time of the optimal mission assignment scheme; Δt is the time saving by the optimal mission assignment scheme. The simulation time interval is used as the unit of t_1, t_2 and Δt.

TABLE II. RESULTS OF THE DIFFERENT NUMBER OF THE QUADCOPTERS WITH THE DIFFERENT SIZE OF THE FARMLAND

m	n	s_1	s_2	t_1	t_2	Δt
3	30	10:10:10	9:12:9	985	872.6	112.4
4	40	10:10:10:10	8:12:8	786.5	592.4	190.1
5	50	10:10:10:10:10	7:11:14:11:7	858.9	598.6	269.3
6	60	10:10:10:10:10:10	6:11:13:13:11:6	723.5	689.2	34.3

TABLE III. RESULTS OF THE SAME NUMBER OF THE QUADCOPTERS WITH THE DIFFERENT SIZE OF THE FARMLAND

m	n	s_1	s_2	t_1	t_2	Δt
3	30	10:10:10	9:12:9	985	872.6	112.4
3	40	14:13:13	11:18:11	1116.9	1040.9	76
3	50	17:17:16	15:20:15	1110.7	971.9	128.8

As can be observed from TABLEs Ⅱ & Ⅲ, the effect of saving time by using the optimal mission assignment scheme is significant whether when the number of the quadcopters is the same but the size of the farmland is different or when the number of the quadcopters is the different and the size of the farmland is different.

V. CONCLUSION

This paper proposes a new mission assignment scheme aimed at the farmland spraying problem. A simulation platform is established and a series of simulations are carried out to verify the reasonability and correctness of this scheme. This scheme mainly solves the mission assignment problem when use the plant-protection-quadcopters to spray pesticides on a rectangular field, and its purpose is to minimize the time to complete the spraying mission. The results of this paper prove that, by using the optimal mission assignment scheme, the mission execution will be more efficient and the mission time of each quadcopter will be close to each other. Although this scheme has some ideal simulation results in this paper, there are still some aspects need to be improved. Firstly, most of the actual farmland is not rectangular and this scheme only suitable for the rectangular farmland. Thus, this scheme needs to be improved to apply to the irregular farmland. Secondly, a quadcopter may suddenly be damaged and unable to work in practice. Thus, this scheme should also consider quadcopter failures in future research.

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