Research on the Design and Path Planning of Child-mother UAV System for Search Task

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Abstract. UAVs are suitable for performing Dull, Dirty and Dangerous tasks due to their small size, strong flexibility and good concealment. The search task is one of the most typical tasks of drones. However, due to the limitation of technology and cost, the existing UAVs usually have one or more restrictions on flight time, flexibility and versatility. This creates certain restrictions for UAVs to perform different types of search tasks in different situations. In order to improve this situation, this paper proposes a search task-oriented unmanned aerial vehicle system, and designs the workflow to adapt to different types of search tasks. And according to the characteristics of the task, different types of path planning methods are designed for the mother UAV and sub-UAV respectively in order to improve the autonomy of the system. Finally, simulation experiments are carried out on MATLAB software to verify the effectiveness of these two methods, and the conclusion and the next work of the system are given.

1. Introduction
With the continuous development of science and technology, UAV has a large number of important applications in military and civil fields. The unique advantages of the UAV itself, such as no casualties, small size and good concealment, make it especially suitable for Dull, Dirty and Dangerous tasks. Searching or cruising in designated areas is a typical task of UAVs. However, due to the limitation of technology and cost, the existing UAVs usually have one or more restrictions on flight time, flexibility and versatility. This creates certain restrictions for UAVs to perform different types of search tasks in different situations. For example, long-endurance UAVs are usually larger and less flexible, while small and flexible UAVs often have low flight speeds and small payloads.

At present, the development of photoelectric payloads carried on UAVs is mature enough, and research on UAV search problems needs to focus on solving UAV path planning issues. The problem of UAV path planning is to use the path planning algorithm to find a set of path points suitable for flight and meet certain constraints[1]. According to different combat missions of UAVs, the path planning methods are also different. For example, when performing cruises or mapping, the main problem of UAV is to find the optimal path able to fully cover a given Region of Interest (ROI). This problem is referred to as coverage path planning (CPP)[2]. Well-known coverage strategies include the boustrophedon decomposition coverage with the back-and-forth motion[3], spiral path coverage[4], and spanning-tree based coverage[5]. There is also a common path planning, that is, given the starting point and target point of the UAV, the optimal path with the least cost is planned for the UAV based on obstacles, fuel consumption, wind speed and other influencing factors. Common path planning
algorithms include: particle swarm algorithm[6], ant colony algorithm[7] and A-star algorithm[8]. The above algorithms can plan the best path for the UAV in a two-dimensional environment, but the development in a complex three-dimensional environment is not perfect. Therefore, the UAV 3D path planning has broad application prospects and more Practicality.

The main work of this paper is as follows:
1. In order to improve the current limitations of UAVs when performing different types of search tasks in different scenarios, a composite UAV system that combines the advantages of the two types of UAV is designed, and design the workflow based on the search tasks features;
2. Applying an area coverage search method that considers the starting point and the end point, and quickly planning the path for mother UAV to cover the ROI with the shortest time cost, and simulation to verify its effectiveness;
3. Aiming at the low-altitude search characteristics of the system’s sub-UAV, a method for obtaining the best path in a complex three-dimensional environment is designed for sub-UAV, and simulation is performed to verify its effectiveness.

2. Design of child-mother UAV system
In this section, the workflow of the system is designed according to the characteristics of the task, so that it can adapt to the search task in multi situation.

2.1. The basic composition of the system
The UAVs currently used for search tasks mainly include micro unmanned rotorcrafts and fixed-wing UAVs. In actual missions, fixed-wing UAVs are usually larger in size, with better payload, flight speed and endurance than micro unmanned rotorcrafts, and are usually used for tasks such as surveying and mapping and high-altitude search. Micro unmanned rotorcrafts have low flying speeds and usually perform short-time low-altitude searches. Their flexible and compact characteristics make them more maneuverable in performing search tasks.

In order to combine the advantages of these two types of UAVs to complete a more efficient search task, this paper combines the vertical take-off and landing (VTOL) UAV and the small rotary wing UAV into a new type of search task-oriented UAV system. The basic composition of the system is shown in Figure 1. It consists of a ground station, a VTOL UAV, a multi-rotor UAV and a special take-off and landing platform for the sub-UAV.

![Fig.1. The composition of child-mother UAV system](image)

The VTOL UAV is the “hybrid” of the rotary wing UAV and the fixed-wing UAV. It has excellent vertical take-off and landing capabilities and high-speed and efficient cruise capabilities. As the mother UAV of the system, it can carry different types of high-precision sensor equipment according to different tasks, and is responsible for reconnaissance and search tasks in designated areas. The multi-rotor UAV has the advantages of vertical take-off and landing, fixed-point hovering, low cost and strong operational advantages. In this system, it receives instructions from mother UAV or ground station to perform close reconnaissance, deterrence or rapid strikes on targets, and even “suicidal” strikes on targets when necessary.
The ground station is responsible for the overall planning of the task, monitors the status of the dual-aircraft system in real time, receives the images returned from UAVs, and issues instructions to the drone based on the actual situation. A small take-off and landing platform is also set up between the VTOL UAV and the rotary-wing UAV, which is mainly responsible for assisting the integration and separation of the two aircraft. The most important role of the platform is to provide guidance for the landing of the rotorcraft.

2.2. The workflow design of the system

According to the characteristics of the system and search tasks, the system has three key links in the execution of tasks: the mother UAV’s coverage search of ROI, the sub-UAV leaving the mother UAV for low-altitude search, and the combination of the mother UAV and sub-UAV.

After the mission begins, the dual-aircraft system will search the active area of the moving target without omissions based on the track planned by the ground station, and use the optical/infrared sensor configured by the mother UAV to conduct a large-area and rapid search over a wide area. During the execution of the task, the mother UAV can also send back the search situation to the ground station in real time, which is convenient for ground personnel to judge the situation and understand the terrain. After finding the target, the mother UAV will release its sub-UAV to conduct a low-altitude search in order to obtain more detailed information. After a low-altitude search mission is completed or when energy is insufficient, the two aircraft will automatically recombine and choose to return to home or start the next mission cycle according to the mission completion status and the ground station’s instructions. This method of searching and hunting in cooperation between the air and the ground can greatly improve the search efficiency in a wide area, reduce the consumption of manpower and material resources, and reduce the risk of the mission to a certain extent. The working diagram and workflow of the system are shown in Figure 2 and Figure 3.

3. Path planning method

This section introduces an area coverage path planning method suitable for the mother UAV of the system, and designs a path planning method based on A-star algorithm for the sub-UAV in the complex three-dimensional environment.

3.1. CPP for the mother UAV

For the mother UAV of the system, the most important task is to perform an exhaustive coverage search for a given search area. And energy is limited. In order to enable the UAV to complete the coverage search of the designated area under the constraints of energy, the altitude of the mother UAV remains basically unchanged when cruising in the air. Therefore, the altitude change can be ignored during
trajectory planning, thus we only need to plan coverage path in two-dimensional for the mother UAV. The range of the UAV’s lateral detection angle when performing search tasks, that is, the UAV’s scan width \( U_x \) is related to the UAV’s flight height \( h \), sensor tilt angle \( \alpha \), and maximum lateral detection angle \( \gamma \). The formula can be expressed as:

\[
U_x = \frac{2h \tan \gamma}{\sin \alpha}
\]  

(1)

In order to search the target area without omission, the distance \( D_x \) between the two flight lines of the UAV should be less than or equal to the scan width \( U_x \) of the UAV. This paper applies the method proposed in the article[9] to plan the best coverage search path on convex polygon ROI for the mother UAV of the system. This method can plan the best path that can cover the target area in a short time when considering the starting point and the end point, thereby minimizing the coverage energy. First, use SHON’s “rotating caliper algorithm” to calculate all the enantiomers of the convex polygon area, and then compare the minimum width of the polygon by rotating the caliper clockwise and counterclockwise on the given enantiomer, and you will be able to get the minimum width set parallel lines as support lines, and finally perform back-and-forth path (BFP) on this basis to obtain the area coverage path with the least time cost.

3.2. 3D path planning for sub-UAV

After the mother UAV finds the target, sub-UAV needs to leave the mother UAV and approach the target point to explore the surrounding environment of the target while flying at low altitude. According to the characteristics of its mission, it needs to carry out point-to-point path planning to avoid obstacles and with the least cost. In order to make the path planning more practical, this paper uses the A-star algorithm to perform point-to-point optimal path planning for the sub-UAV in a complex three-dimensional environment with obstacles/no-fly zones. The basic principle of the A-star algorithm is to first select an appropriate heuristic function according to the search environment, estimate the cost value from the search neighborhood to the current point, select the point with the least cost as the next track point, and gradually search from the start point to the end point, and finally backtracking the parent node of the current node to generate the global optimal path with the least cost, where the OPEN list is used to store the track nodes to be expanded, and the CLOSE list is used to store the expanded track nodes. The cost function is:

\[
f(n) = g(n) + h(n)
\]  

(2)

Among them, \( g(n) \) represents the actual cost from the starting point to any node \( n \), \( h(n) \) represents the heuristic estimated cost from node \( n \) to the target point. In order to realize the search of the A-star algorithm in a three-dimensional environment, this paper builds a three-dimensional map based on DEM data, and Obstacles/no-fly zones are set above. When using the A-star algorithm, expand the current node \( n \) to the target point from eight directions in the two-dimensional to 25 directions in the three-dimensional space. Second, the heuristic function is the core of A-star algorithm. Widely used heuristic functions are Manhattan distance, diagonal distance and Euclidean distance. In order to adapt to the complex three-dimensional search environment, this paper uses Euclidean distance, its expression is:

\[
h(n) = \sqrt{(x_n - x_g)^2 + (y_n - y_g)^2 + (z_n - z_g)^2}
\]  

(3)

4. Experiment and analysis

In this section, two different types of path planning methods are proposed to simulate on MATLAB software, and the results are analyzed to verify their effectiveness.

4.1. Simulation experiment of coverage path planning for the mother UAV

According to the workflow of the whole system, first of all, it is necessary to carry out the path planning of area coverage for the mother UAV.
The experimental parameters and time cost calculated by experiment are shown in Table 1. In simulation experiments, parameters such as distance between flight lines, forward speed, flight altitude, start point and end point of the task need to be set to simulate the host’s coverage search for random polygon ROI areas, and finally the time cost is evaluated from the planned coverage path. In this paper, we assume that the ROI is a convex polygon, and use the region coverage method to get the path for the mother UAV which can cover the ROI in the shortest time. Three polygons, Q1, Q2, Q3, are generated randomly. Using this method, coverage paths are generated in these three areas, and the cost of coverage time is calculated. The experimental results of coverage path planning are shown in Figure 4.

From the experimental results, it can be seen that this method can quickly plan the area coverage path according to different starting point, end point and different shape of ROI, and give the time cost, which has greater reference significance for the actual planning.

### Table 1 Parameters used in the experiments and time cost calculated by experiments

| Item   | Distance between flight lines | Forward speed | Flight altitude | Start point          | End point          | Time cost    |
|--------|-------------------------------|---------------|-----------------|----------------------|---------------------|--------------|
| Q1     | 1400 m                        | 20 m/s        | 500 m           | (-10000,-10000)     | (-10000,-10000)    | 11096.426s   |
| Q2     | 1400 m                        | 20 m/s        | 500 m           | (-10000,-10000)     | (9000,9000)        | 10257.277s   |
| Q3     | 800 m                         | 20 m/s        | 300 m           | (-10000,-10000)     | (-10000,-10000)    | 22037.1473s  |

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In this paper, we assume that the ROI is a convex polygon, and use the region coverage method to get the path for the mother UAV which can cover the ROI in the shortest time. Three polygons, Q1, Q2, Q3, are generated randomly. Using this method, coverage paths are generated in these three areas, and the cost of coverage time is calculated. The experimental results of coverage path planning are shown in Figure 4.

4.2. Simulation experiment of 3D path planning for sub-UAV

Different from the mother UAV, sub-UAV focuses on the low altitude point-to-point obstacle avoidance path planning. In order to simplify the route planning process, the following assumptions are proposed in this paper:

- The threat area in 3D environment is consistent with terrain information;
- Neglecting meteorological interference, mechanical dynamics and other factors;
- There is a linear relationship between fuel consumption and flight distance of UAV;
- The UAV maintains a constant flight speed.

Import the responsible 3D terrain data and set a certain number of obstacles, so as to simulate the complex 3D flight environment for the sub-UAV of the system. The algorithm designed in this paper is used to plan the global optimal obstacle avoidance path for the sub-UAV of the system. The simulation results of path planning are shown in Figure 5. It can be seen from the results that this method can...
successfully plan the optimal path to avoid obstacles for the sub-UAV in the complex three-dimensional environment.

Fig.5. Simulation results of 3D path planning

5. Conclusions and Future Work

The child-mother UAV system proposed in this paper has a great application prospect in search mission. It combines the advantages of vertical take-off and landing UAV and the small rotary wing UAV and the special workflow makes it more efficient in search task. The two types of UAV path planning methods proposed in this paper can be realized in the simulation experiment, which is conducive to improving the autonomy of the system to complete the search task. The next step is to apply the path planning method to practice, and verify the feasibility of the system in the actual execution of the search task combined with the workflow.

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