Fast Path Planning for Firefighting UAV Based on A-Star algorithm

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Abstract. When the long distance oil-gas pipeline accident occurs, the fire UAV can give priority to the place where the accident occurs. Emergency investigation and fire rescue, greatly reduces the harm of the accident. However, due to the limitation of the UAV navigation system, the UAV will accumulate the positioning errors over time in the flight process. If the positioning errors can not be corrected in time, it will make the UAV unable to reach the intended destination, thus leading to the failure of the rescue mission. In view of this phenomenon, we propose a UAV path planning scheme considering positioning errors. Taking the UAV’s total flight path as short as possible and errors correction points as few as possible, a multi-objective programming model is established considering errors correction constraints and path constraints. The Euler distance with coefficient is selected as the estimated cost function of A-Star algorithm, and the optimal flight path of UAV is quickly planned through heuristic search. Taking the data of a certain flight area as an example, we have simulation results showing that the A-Star algorithm can quickly and effectively solve the problem of UAV flight path planning considering positioning errors.

1. Introduction
When carrying out rescue missions, firefighting UAV must be accurate and fast to reach the destination. This puts forward a certain requirement for the navigation accuracy of UAV. At present, the navigation technologies mainly used by UAV include inertial navigation, satellite navigation, geomagnetic navigation and terrain aided navigation [1]. However, in the complex terrain and bad weather, the UAV often can only use inertial navigation technology. There are some positioning errors when the UAV adopts the inertial navigation technology. They are the errors accumulated over time due to the inability of the UAV to accurately position itself during flight, including vertical errors and horizontal errors.

In recent years, the researches of UAV path planning mainly focus on the danger avoidance and mission requirements, and there are few researches on the path planning with positioning errors as the constraint conditions. Chen Chang applied the optimized A-Star algorithm to the global and local path planning of the UAV, which shortened the path length and pathfinding time, and improved the smoothness of the path. This method is suitable for the multi-obstacle avoidance of the UAV path planning [2]. Jianlin Xin used Dijkstra algorithm to initialize the flight path, and adopted multi-path selection strategy and simulated annealing mechanism to improve the global search ability, which improved the flight path planning ability of UAV in danger avoidance and complex environment [3]. Chengzhen Wu constructed the mathematical model of UAV under the constraint of positioning...
errors, deduced the spatial arc trajectory equation by combining the path points and turning radius, and used the greedy algorithm to quickly plan the path of UAV. They provided ideas for the application of warehouse logistics path planning [4]. Xiaohui Li used the improved A-Star algorithm and combined with various types of no-fly zones to plan the optimal flight path for the UAV to avoid obstacles between two customer points. This method can effectively solve the obstacle avoidance path planning problem of UAV in the coexistence of multiple types of no-fly zones [5]. To sum up, the research on UAV path planning with positioning errors as the constraint conditions is relatively shallow, so we designed a UAV path fast planning scheme based on A-Star algorithm under the positioning constraint conditions [6].

2. Path planning considering positioning errors

2.1. Problem description

It is known that the UAV needs to start from Station A to Station B to complete the rescue mission. There are several horizontal correction points and vertical correction points within the space range of AB, and the positions and types of each correction point are known.

The horizontal errors and vertical errors will each increase by $\delta$ units for each meter the UAV flies. When starting from Station A, both the horizontal and vertical errors of the UAV are 0. When the UAV reaches the horizontal correction point, if the vertical errors are no more than $\beta_1$ units and the horizontal errors are no more than $\beta_2$ units, the horizontal errors of the UAV can be corrected. After the correction, the horizontal errors become 0 and the vertical errors remain unchanged. When the UAV reaches the vertical correction point, if the vertical errors are not more than $\alpha_1$ units and the horizontal errors are not more than $\alpha_2$ units, the vertical errors can be corrected. After correction, the vertical errors become 0, while the horizontal errors remain unchanged. When the UAV arrives at Station B, if its vertical and horizontal errors are both less than $\theta$ units, it is considered that the UAV's path planning is successful [7]. Our goal is to quickly planning out a path that would allow the UAV to reach Station B with the shortest possible distance and with the fewest possible correction points.

2.2. Establishment of mathematical model

2.2.1. The establishment of the objective function

The path to be planned can be divided into three parts, as shown in Figure 1.

![Figure 1. Path analysis diagram](image)

Assume that the UAV will pass through N points in this section of the path, and the definition set S represents the points that the UAV passes through $S = \{A, N_1, N_2, ..., N_k, B\}$. As shown in Figure 1, the distance between A
and $N_i$ is: $d(A, N_i) = L_i$. The distance between $N_i$ and $N_{i+1}$ is: $d(N_i, N_{i+1})$. The distance between $N_k$ and B is: $d(N_k, B)$. Then, the first objective function with the shortest possible path is shown in Equation (1).

$$L_{\text{min}} = \min \sum_{i=1}^{k} d(N_i, N_{i+1}) + d(A, N_i) + d(N_k, B) \quad (1)$$

The second objective function indicates that the number of correction points passed are as few as possible, so it can be expressed as $\min S_I$. According to the weighted coefficient method, a coefficient is assigned to each objective, and the multi-objective programming model is transformed into a single objective programming model. The model is shown in Equation (2).

$$F = \min [\lambda \sum_{i=1}^{k} d(N_i, N_{i+1}) + d(A, N_i) + d(N_k, B) + (1 - \lambda) S_I] \quad (2)$$

Due to the different units of measurement of each index in the model, it is necessary to standardize the index and map its value to a certain value interval through function transformation. The standardization processing formula is shown in Equation (3).

$$Z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \quad (3)$$

2.2.2. Constraint conditions

(1) The constraints between A and $N_1$

When the UAV reaches $N_1$, the constraint conditions for vertical correction or horizontal correction are shown in Equation (4) or (5):

$$\begin{cases} d(A, N_1) \cdot \delta_v \leq \alpha_1 \\ d(A, N_1) \cdot \delta_h \leq \alpha_2 \end{cases} \quad (4) \quad \begin{cases} d(A, N_1) \cdot \delta_v \leq \beta_1 \\ d(A, N_1) \cdot \delta_h \leq \beta_2 \end{cases} \quad (5)$$

(2) The constraints between $N_i$ and $N_k$

If the UAV has been corrected for horizontal errors at $N_i$, the constraint conditions for vertical errors correction at $N_2$ are shown in Equation (6); If the UAV has been corrected for vertical errors at $N_i$, the constraint conditions for horizontal errors correction at $N_2$ are shown in Equation (7):

$$\begin{cases} d(N_i, N_j) \cdot \delta \leq \alpha_1 \\ d(A, N_i) \cdot \delta + d(N_i, N_2) \cdot \delta \leq \alpha_2 \end{cases} \quad (6) \quad \begin{cases} d(N_i, N_j) \cdot \delta \leq \beta_1 \\ d(A, N_i) \cdot \delta + d(N_i, N_2) \cdot \delta \leq \beta_2 \end{cases} \quad (7)$$

The above method is applicable to $N_i$ point to $N_{i+1}$ point searching. Then, the constraint conditions for errors correction at any point are shown in Equation (8). Where, $e_{N_i}$ represents the errors of UAV after horizontal or vertical errors correction at $N_i$.

$$\begin{cases} d(N_i, N_{i+1}) \cdot \delta \leq \alpha_i \\ d(N_i, N_{i+1}) \cdot \delta + \sum_{i=1}^{k} e_{N_i} \leq \alpha_2 \end{cases} \quad \text{or} \quad \begin{cases} d(N_i, N_{i+1}) \cdot \delta \leq \beta_i \\ d(N_i, N_{i+1}) \cdot \delta + \sum_{i=1}^{k} e_{N_i} \leq \beta_2 \end{cases} \quad (8)$$

(3) The constraints between $N_k$ and B

When the UAV arrives at Station B, both vertical and horizontal errors should be less than $\theta$ units, and there will be errors in only one direction at the point $N_k$, so the constraint conditions are shown in (9).

$$e_{N_k} + d(N_k, B) \cdot \delta \leq \theta \quad (9)$$
3. Algorithm design of A-Star

A-Star algorithm is a heuristic algorithm in artificial intelligence, which realizes optimization through regular expansion of the smallest points of the estimation function [8]. The estimation function set in this paper is shown in (10).

\[ D_{\text{min}} = d(N_i, N_{i+1}) + \eta d(N_{i+1}, B) \quad \eta > 1 \quad (10) \]

Among them: \( d(N_i, N_{i+1}) \) is the Actual cost between \( N_i \) and \( N_{i+1} \). \( \eta d(N_{i+1}, B) \) is the Estimated cost. The flow chart of path planning using this algorithm is shown in Figure 2.

![Algorithm flow chart](image)

Figure 2. Algorithm flow chart

The search radius of UAV is that: The UAV can not exceed \( \frac{\theta}{\delta} \) the single flight distance, otherwise the positioning error cannot be corrected.

The selection of the Estimated cost function is very important for the whole algorithm, which determines the search direction of each step of the algorithm and affects the search efficiency and solving
5. The precision of the algorithm. The classical A-Star algorithm uses Euclidean distance or Manhattan distance to represent the estimated cost. In this paper, some minor improvements are made to the estimation cost function, and the influence is adjusted by setting the coefficient, which makes the algorithm more flexible to solve the optimal flight path.

4. The simulation analysis
It is known that there are a total of 611 correction points in a certain flight area, among which the spatial coordinates and correction types of each correction point are known. We set $\alpha_1 = 25, \alpha_2 = 15, \beta_1 = 20, \beta_2 = 25, \theta = 30, \delta = 0.001$ [9]. The information of some correction points in the flight area is shown in Table 1. About the type of correction point in the table, 1: represents the vertical correction point; 0: represents the horizontal correction point.

| Serial number | X     | Y     | Z     | Type |
|---------------|-------|-------|-------|------|
| 1             | 0.00  | 50000.00 | 5000.00 | A    |
| 2             | 33070.83 | 2789.48 | 5163.52 | 0    |
| 3             | 54832.89 | 49179.22 | 1448.30 | 1    |
| ...           | ...   | ...   | ...   | ...  |
| 611           | 14870.60 | 95939.17 | 8248.84 | 0    |
| 612           | 93009.57 | 4549.33 | 7882.61 | 1    |
| 613           | 100000.00 | 59652.34 | 5022.00 | B    |

MATLAB programming is used to realize the above algorithm, the error correction information is shown in Table 2.

| Serial number | Vertical errors | Horizontal errors | Type |
|---------------|-----------------|------------------|------|
| 1             | 0               | 0                | A    |
| 522           | 9.6265          | 9.6265           | 0    |
| 65            | 21.7554         | 12.1289          | 1    |
| 81            | 11.4211         | 23.55            | 0    |
| 171           | 23.3981         | 11.9771          | 1    |
| 279           | 10.457          | 22.4341          | 0    |
| 370           | 21.8932         | 11.4361          | 1    |
| 215           | 13.3136         | 24.7497          | 0    |
| 398           | 22.3307         | 9.0171           | 1    |
| 613           | 16.9727         | 25.9898          | B    |

The path length is solved as a result of 106350.06; the number of corrected points is 8. The results meet the restriction requirements of the constraint conditions [10]. The A-Star algorithm is compared with Dijkstra algorithm, and the comparison results are shown in Table 3.

It can be seen from the Table 3 that A-Star algorithm is superior to Dijkstra algorithm both in terms of algorithm accuracy and running time. This indicates that the UAV path planning method based on A-Star algorithm is more suitable for solving the problem of firefighting UAV path planning constrained by positioning errors.
Table 3. Comparison of algorithm performance

| Algorithm | Number of correction points | The length of the path (m) | Running time (s) |
|-----------|-----------------------------|---------------------------|------------------|
| Dijkstra  | 9                           | 111286.498                | 1.31             |
| A-Star    | 8                           | 106350.06                 | 0.291            |

5. Conclusion
In this paper, the path planning problem of firefighting UAV with positioning errors constraint is taken as the starting point, and the multi-constraint path planning problem of UAV based on A-Star algorithm is emphatically studied. The innovation point is that the positioning errors are combined with the flight path planning, and the A-Star algorithm is used to solve the fast flight path planning problem of the firefighting UAV. The performance of A-Star algorithm and Dijkstra algorithm is compared, and it is concluded that A-Star algorithm has certain advantages in solving this problem. The model and algorithm presented in this paper provide a theoretical basis for the rapid flight path planning of UAV.

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