Research Status of Autonomous Obstacle Avoidance System for Unmanned Aerial Vehicles

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***Abstract*—Civilian Unmanned Aerial Vehicles (UAVs) are widely used in environmental monitoring, search and rescue, traffic monitoring, logistics and freight transportation, agriculture, forestry and plant protection, aerial photography, urban inspection, remote sensing detection, and other fields. The operation in low-altitude environments poses a greater challenge to the safety of UAVs autonomous flight technology, and the key to ensuring the safe and autonomous flight of UAVs is the autonomous obstacle avoidance algorithm, which has also received a lot of attention. Obstacle avoidance path planning for UAVs is to find a flight path that makes the UAVs follow an optimal flight path from the starting point to the target point under a specific task background. In the face of special tasks, a single UAV may be unable to complete it. At this time, the mode of multiple UAVs performing functions simultaneously has been developed and widely used. This paper will sort out and review the research on UAV obstacle avoidance algorithms. In this paper, the discussion will be divided into two types of subjects: a single UAV and multiple UAVs. And the algorithm of a single UAV is divided into global obstacle avoidance and local obstacle avoidance.**

***Keywords*—Unmanned Aerial Vehicles (UAVs), algorithm, obstacle avoidance**

I. INTRODUCTION

As an important carrier of advanced productivity, civilian Unmanned Aerial Vehicles (UAVs) are widely used in environmental monitoring, search and rescue, traffic monitoring, logistics, freight transportation, agriculture, forestry and plant protection, aerial photography, urban inspection, remote sensing detection, and other fields. The main reasons for the wide application of UAVs are their simple hardware manufacturing, low cost, and mature control algorithm. In addition, it can also avoid the influence of pilot physiological problems.

However, when UAVs are concentrated in low-altitude airspace, the UAV running alone or with the human machine not only has to face static obstacles such as terrain, buildings, and other dynamic obstacles but also faces other aircraft in the airspace [1]. Therefore, the operation in low altitude environments poses a greater challenge to the safety of UAVs autonomous flight technology, and the key to ensuring the safe and autonomous flight of UAVs is the autonomous obstacle avoidance algorithm, which has also received a lot of attention.

Obstacle avoidance path planning for UAVs is to find a flight path that makes the UAVs follow an optimal flight path from the starting point to the target point under a specific task background. This flight path should meet the physical constraints of UAVs themselves and should be able to safely avoid obstacles and threats. Therefore, having efficient obstacle avoidance ability has become one of the important guarantees for UAVs to safely complete flight tasks.

Under the existing UAV architecture, obstacle avoidance requirements in the complex environment of low-altitude airspace, such as modern high-rise cities, jungles, farmland, indoor environments of complex buildings, road traffic, and military battlefields, also need different types of algorithms and hardware facilities to cope with them. Therefore, the market demand for obstacle avoidance is increasing, but due to the increasing difficulty of the task, the usage of UAVs is also expanding. In the face of special tasks, a single UAV may not be able to complete it. At this time, the mode of multiple UAVs performing tasks at the same time has been developed and widely used [2].

Aiming at the problem of UAV obstacle avoidance, a lot of solutions have been proposed in the literature from different perspectives. This paper will sort out and review the research on UAV obstacle avoidance algorithms. In this paper, the discussion will be divided into two types of subjects: a single UAV and multiple UAVs [2]. The algorithm of a single UAV is divided into global obstacle avoidance and local obstacle avoidance [3]. Among them, this paper will introduce some common obstacle avoidance algorithms in the above two categories, focusing on the basic principles of obstacle avoidance methods and analyzing their respective advantages and disadvantages, to provide reference for further research.

II. BACKGROUND ON ALGORITHMS AND AVOIDANCE TECHNOLOGY

A. Global Planning Algorithm

The global planning algorithm (obstacle avoidance method based on path planning algorithm is also called global planning obstacle avoidance) includes A* Algorithm, Fast Random Expansion Tree (RRT) algorithm, and Genetic algorithm. It gives an overview of them as follows.

1) A* searching algorithm

A* search algorithm is a classical search algorithm for finding the optimal path in a static connected graph according to the evaluation function, and it is also the most effective direct search algorithm. According to Lim *et al.* [4], the sparse A* algorithm is used to simplify the constraints of UAVs, reduce the search space, and effectively shorten the time of route planning. Li *et al.* propose A planning method combining an improved bidirectional A* algorithm and vector field histogram algorithm, which shortens the planning time and path compared with the traditional A* algorithm [5].

This section introduces the main steps in the A* search briefly. Firstly, the flight space is decomposed into some cells with regular shapes by grid method, and whether these cells are covered by obstacles or intersect with obstacles is judged. Then, the cells containing the starting point and the goal point are found, and the A* algorithm is used to find them [3].

A series of connected units are found to connect the starting unit and the target unit. The search process of the A* algorithm is carried out in the direction of low cost according to the value of the heuristic function, that is, for node n, the algorithm uses the cost function to evaluate its surrounding nodes and selects the point with the minimum estimated value as the next node [3].

The cost function is expressed as follows:

$$f(n) = g(n) + h(n)$$

where h(n) is the heuristic function; g(n) is the predicted cost from the current node position n to the target point and it is the route cost from the starting point to the current node n. f(n) is the estimated value, which is obtained by adding h(n) and g(n). In raster graphs, the heuristic function h(n) is usually represented by the distance between two points. The calculation process of the A* algorithm is a process of exploration. By gradually extending the direction of the minimum f(n), the optimal solution is gradually obtained, which is the optimal route.

2) RRT algorithm

Rapidly-exploring Random Tree (RRT) is a sampling-based single query random search algorithm, which can quickly and effectively search and plan the path according to the current environmental information and can deal with the complex dynamics and kinematic constraints of UAVs.

The RRT algorithm takes the starting point in the state space as the root node. Then the random expansion tree is generated by randomly adding leaf nodes gradually. During the generation process, if the new node conflicts with the obstacle area, the node is discarded and selected again. When the target point is included in the leaf nodes of the random tree, the expansion of the random tree stops and an obstacle avoidance route from the starting point to the target point can be obtained. Lu *et al.* [6] designed an online route planning algorithm based on the RRT algorithm for a certain type of UAVs and verified the feasibility of the method through simulation. Yin *et al.* [7] overcome the traditional RRT by introducing the track distance constraint to make the search tree expand along the approximate optimal track direction with the shortest path. The expansion of the random tree is shown in Fig. 1 and the specific process of RRT algorithm obstacle avoidance implementation is given as follows:

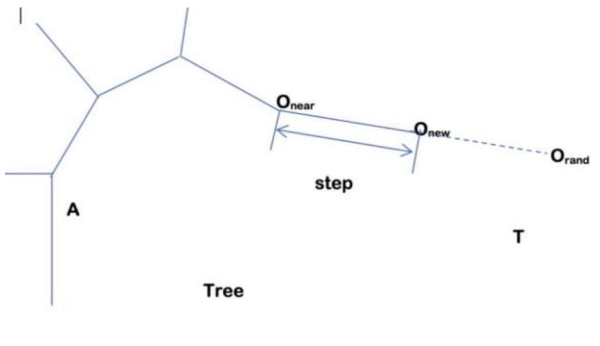

Fig. 1. Schematic diagram of RRT node expansion.

In Fig. 1, A and T are the starting and target points, respectively, and Orand is a random sampling point in the state space. The selection rule of Orand is as follows: the target point T is selected with probability p, and a point Orand is randomly selected in the flight space with probability 1−p. Onear is denoted as the node closest to the random sampling point Orand in the leaf node of the random tree, and then a new node Onew is intercepted on the line between Orand and Onear in the unit of expansion step. If no obstacles are encountered in the process of expanding to the new node, Then the new node Onew is added to the random tree, otherwise, the node is discarded, and the random sampling point Orand needs to be selected again. Through this successive iteration, until the leaf node in the random tree is close enough to the target point T, the loop ends.

3) Genetic algorithm

A genetic algorithm is an optimization algorithm inspired by the idea of biological evolution. It has a powerful global search ability and can solve the problem of route planning well. Research by Yang [8] claims an improved genetic algorithm, which can effectively solve the multi-objective route planning problem in a static environment compared with the traditional genetic algorithm. According to Ma & Zhou [9], the genetic algorithm based on chaos was used to solve the UAV route planning problem, which shortened the path coding length and improved the search efficiency. Lv *et al.* [10] added the operation of deleting nodes to avoid redundant waypoints and proved that the path generated by this method is smoother and safer through simulation comparison.

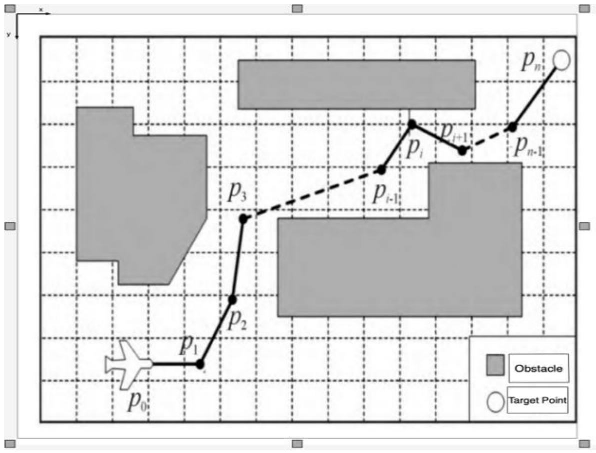

Fig. 2. Schematic diagram of random generation path.

A genetic algorithm is a stochastic optimization search algorithm summarized based on the use of biological evolution in nature. The basic idea of a genetic algorithm is to divide the flight space by grid method and find the area covered by obstacles or conflict with obstacles. Then randomly generate a collision-free path Pl from the starting point to the goal in the map. From Fig. 2, the path PI can be expressed as:

$$PI = \{p0, p1, p2, ... pi\text{-}1, pi, pi +1, ..., pn\} \quad (1)$$

In Eq. (1), p0 represents the starting point; pn represents the target point; pi represents the ith path node in the whole path; pi-1, pi denotes the ith path segment.

B. Local Obstacle Avoidance Algorithms

However, the global algorithm starts with a high-level outline of the route. In the actual operation, there may be some obstacles that have not been planned before and some dynamic obstacles as well. Therefore, some local obstacle avoidance algorithms emerged.

1) Obstacle avoidance method based on local anti-collision algorithms

The obstacle avoidance method based on a local anti-collision algorithm is also called local planning obstacle avoidance, which refers to the use of the local anti-collision controller of UAVs to avoid the detected obstacles in real-time. This kind of method does not rely on global information and does not need to know the information of the initial point and the target point, only needs the real-time obstacle information detected by the UAV sensor. It is mostly used for obstacles with insufficient prior information or sudden obstacles, such as enemy missiles, early warning aircraft, etc. Such methods usually rely on the UAV navigation control system, which can be a part of the control loop or a separate inner loop [11]. The obstacle avoidance method based on the local anti-collision algorithm mainly includes the obstacle avoidance algorithm based on the guidance law method, the obstacle avoidance algorithm based on the velocity obstacle method, and the obstacle avoidance algorithm based on the artificial potential field method. This section gives an overview of the first two as follows.

The guidance law based on the approach

The obstacle avoidance algorithm based on guidance law uses local obstacle information to calculate the guidance commands required for obstacle avoidance. It can also be regarded as a UAV guidance method with an obstacle avoidance function, which uses the obstacle information detected by the UAV to generate acceleration commands in real-time to avoid obstacles. The basic idea is to integrate and analyze the obstacle information detected by sensors during flight, and according to the requirements of obstacle avoidance, the obstacle covering circle and the combination model of covering circle are established to replace the complex obstacles.

The route tracking guidance method could be optimized also, and the timing of avoidance guidance and the reference point selection principle were determined, which could make the UAV deviate from the original route slightly while avoiding obstacles [13] claimed that fuzzy rules were established by using the information of UAV and obstacles, and guidance instructions required for UAV obstacle avoidance were obtained through fuzzy control, which was suitable for two-dimensional plane obstacle avoidance. Guo *et al.* [14] designed an arc obstacle avoidance path according to the obstacle model and realized three-dimensional path tracking and obstacle avoidance of UAVs by combining them with nonlinear guidance law.

Velocity obstacle method

The obstacle avoidance algorithm based on the velocity obstacle method uses the velocity space model to convert the obstacle range in the physical space to the velocity space as to solve the velocity output of UAVs when avoiding obstacles. The velocity obstacle method mainly considers obstacle avoidance for moving obstacles, and its basic idea is to convert the achievable range of obstacles in physical space to velocity, from which the feasible solution of the UAV in the velocity space can be obtained. The research by Zhang [15] established a three-dimensional dynamic uncertain velocity obstacle model, and the effectiveness and feasibility of the method were verified by simulation. Liu *et al.* [3] improves the velocity obstacle method, and compared with the traditional velocity obstacle method, it can realize the obstacle avoidance of UAVs in dense scenes.

The obstacle avoidance algorithm based on the artificial potential field method uses the virtual potential field to generate the attraction and repulsion force on the UAV and introduces the resultant force of the attraction and repulsion force into the bottom control as to obtain an effective local obstacle avoidance route. In [16], the artificial potential field method was improved to make it have a smaller track deviation than the traditional artificial potential field method, and it was verified by simulation. Gu *et al.* [17] claims an artificial potential field based on the Laplace equation, which has high fitness to the obstacle form and can quickly calculate the gradient of any point in the potential field.

The concept of velocity obstacle was first proposed by Fiorini [3], which assumes that in physical space. There is an emptiness at time t and the interval range X, then there exists a corresponding set V in the velocity space corresponding to it. If the UAV starts at time t = 0 and moves with a specific velocity in V, then the position of the UAV must be in X at time t, so that V(t) is an instantaneous velocity obstacle, denoted SVR(t). For an obstacle that exists for a certain time, its velocity obstacle is a two-dimensional graph in the velocity space, and if the obstacle moves at a certain speed, its velocity obstacle is a cone without a tip, denoted as VOS, as shown in Fig. 3.

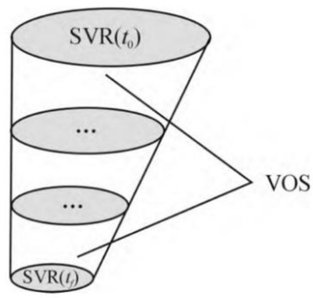

Fig. 3. Schematic diagram of VOS.

In Fig. 3, VOS is obtained when the specific motion path of the obstacle is unknown, which includes all possible motion modes of the obstacle and summarizes the motion range of the obstacle comprehensively. The calculation formula for the velocity obstacle is as follows:

$$Q = \frac{S}{t}$$

In the equation above, Q is the piecewise expression of the speed obstacle range. S is the corresponding physical space obstacle range.

Artificial potential field method

The artificial potential field method was first proposed by Khatib as a virtual force method. The basic idea of the artificial potential field method for obstacle avoidance is to design the motion of the UAV in the flight environment as in a hypothetical artificial force field, where the target point is the UAV. The attractive field is generated, and the obstacle generates a repulsive force field to the UAV. Finally, the UAV generates an obstacle avoidance path in the direction of the potential field descent under the superposition of the gravitational field and the repulsive force field.

C. Cooperative Formation Obstacle Avoidance Method

The above is the case of a single UAV. In the case that the formation members do not change and the formation changes, it is necessary to consider the advantages of different formations according to the requirements of the flight environment. According to flight environment, transformation, considering the advantages of different formation of formation and formation control methods mainly include artificial potential field and obstacle avoidance method based on artificial immunity.

1) Artificial potential field method

The artificial potential field method [18] is widely used in the study of UAV obstacle avoidance, which is simple, practical, and practical in engineering. The artificial potential field method treats UAVs as spheres that attract or repel each other, and according to the relative distance of adjacent UAVs, two virtual forces are proposed, which are formation attraction and formation repulsion.

The artificial potential field method [19] is also suitable for multi-UAV obstacle avoidance. It is a widely used method in the study of UAV obstacle avoidance, which is simple, practical, and practical in engineering. The artificial potential field method treats UAVs as spheres that attract or repel each other, and according to the relative distance of adjacent UAVs, two virtual forces are proposed, which are formation attraction and formation repulsion.

When the UAVs are close to each other within a certain distance range, a formation repulsion force will be generated, which makes the neighboring UAVs move in the opposite direction, to avoid collision. When UAVs are far away from each other within a certain distance range, formation gravity will be generated, and the formation gravity makes adjacent UAVs move toward each other to avoid losing contact among UAVs.

Khatib [19] gave the classical potential energy field function in the reference:

$$U_G(p) = \frac{1}{2}k(p - p_G)^2$$

$$U_O(p) = \begin{cases} \frac{1}{2}\eta(\frac{1}{P} - \frac{1}{P_O})(p \le p_o) \\ 0 \qquad\qquad (p > p_o) \end{cases}$$

where UG(p) is the gravitational field at p; UO(p) is the repulsive force field at p; k > 0 and η > 0 are the coefficients of the gravitational field and the repulsive field, respectively. ρ is the shortest distance between the UAV and the obstacle; Let ρ0 be a one-threshold value. The resultant force of the UAV in the force field can be expressed as follows:

$$\begin{aligned} F(p) &= F_G(p) + \sum_{i=1}^{n} \mathrm{F}_{Oi}(p) \\ &= -\nabla U_G(p) + \sum_{i=1}^{n}(-\nabla U_{Oi}(p)) \end{aligned}$$

In the equation above, FG(p) is the gravitational force generated by the gravitational field of the UAV at point p and is the negative gradient of the gravitational field. Foi(p) is the repulsive force generated by the gravitational field of i obstacles at point p, and the repulsive force is the negative gradient of the repulsive field at point p. The traditional artificial potential field method often suffers from a local minimum problem. When the UAV group reaches a stable formation, each UAV only has the gravitational force provided by the target point.

If the formation encounters an obstacle at this time, the repulsion force of the obstacle is equal to the gravitational force of the target point, then the individuals in the group will face the static problem caused by the local minimum. To solve such problems, an improved artificial potential field method is proposed.

Improved artificial potential field method to solve the problem of local minimum, can adopt the consistency control scheme, to take in the UAV formation will exist in the distributed interactive information strategy due to the formation of unbalanced force due to the same obstacles role UAV, under the action of distributed communication topology, A force will be generated inside the formation so that the stationary UAV will advance under the action of the formation force. The method also has strong stability and flexibility. It can timely change its motion state to adapt to the dynamic environment by exchanging information with the adjacent UAVs.

2) Artificial immune algorithm

The obstacle avoidance method based on artificial immunity [20] was originally used for robot obstacle avoidance and improved for UAV obstacle avoidance. In this obstacle avoidance method, UAVs are defined as B cells, and the number of range sensors that need to be equipped is related to the degree of influence of environmental information in different directions on path planning. The combination of the information detected by the sensors defines the flight direction of UAVs. According to the influence of the obstacle target on the path planning of UAVs, the antigens for obstacles and targets are designed.

The main obstacle avoidance process was that the UAV used sensors to detect the surrounding antigen information, including obstacles and target information, and formed antigen codes. According to the antigen coding and antibody coding, the optimal antibody selection is performed based on the immune network dynamics model, that is, the flight state is selected, to realize the autonomous obstacle avoidance operation of UAVs.

3) Obstacle avoidance method using ADS-B system

Another method is the obstacle avoidance method of two or more UAVs in a common aviation field. The trajectory of the UAV is obtained by approximating two or three trajectory points obtained by the ADS-B system. In the process of determining the intersection point of the trajectory, two cut-off values of the critical speed range where the UAV collision may occur are calculated. Since the calculated expressions for the intersection of the critical velocities and the cutoff values are expressed in analytical form, the computation time is much smaller than the ADS-B receiving data, even if the computational power of the onboard computer system is limited. Thus, at each cycle of receiving new data, the computation can be updated and the trajectory is approximately bounded by a straight line. This approach works even for a significant number of UAVs, more than a few dozen, by developing compact collision avoidance algorithms.

III. Comparison of Obstacle Avoidance Methods

A. Comparative Analysis of Global Obstacle Avoidance Algorithms

The advantages and disadvantages of UAV obstacle avoidance algorithms are mainly reflected in the success rate of obstacle avoidance, path optimality, and computational complexity. For the above-introduced obstacle avoidance algorithms, each algorithm has its advantages and disadvantages, which need to be based on different flight tasks selected, and the following several algorithms are compared and analyzed.

For the route planning algorithm, the A* search algorithm can complete the obstacle avoidance route planning in a short time and obtain a better obstacle avoidance route, but it can only be used for the planning of a static environment. The planning effect of the A* algorithm mainly depends on the selection of a heuristic function [21]. A better heuristic function can obtain a better obstacle avoidance route, but the time required for planning will also increase accordingly. The RRT algorithm avoids modeling the state space by randomly sampling the state space and has efficient search characteristics.

The method based on stochastic programming makes the RRT algorithm able to deal with the complex dynamics and kinematics constraints of UAVs, but the random sampling of nodes also makes the obstacle avoidance route obtained by the algorithm difficult to ensure optimality [7]. Genetic algorithms can obtain the optimal obstacle avoidance path through the repeated iterative screening of elite individuals, which has strong adaptability and robustness [6]. However, the evolution speed is difficult to control, the operation speed is not fast, and it needs large storage space and operation time. The pairs of obstacle avoidance methods based on the route planning algorithm are shown in Table 1.

Table 1. Comparison of route planning algorithms

Types	Advantages	Disadvantages
A* Algorithm	The computational complexity is low, and the planning speed is fast.	It can only be used for static environment planning. It is prone to exponential explosion and highly dependent on the heuristic function.
RRT ALGORITHM	It can deal with the problem of multiple constraints and has good robustness.	The path optimality is poor.
Genetic Algorithm	Genetic algorithm has better path optimality.	It requires a lot of operation time and storage space.

To solve these sorts of problems, [22] adopted the variable step size strategy to improve the search efficiency of the A* algorithm and generate a series of flight paths that meet the physical performance constraints of UAVs such as pitch Angle and yaw Angle. Qi *et al.* [23] improved the A* algorithm from four aspects: target expansion, target visibility judgment, replacement of heuristic function, and change of expansion node selection strategy, which improved the convergence efficiency of the algorithm and optimized the path length. Qi *et al.* [23] combined Dubins with the A* algorithm and used the principle of “vector sharing” to calculate the change of free heading the path replanning is carried out, and the continuous flight safe path can be obtained in a short time.

Given the problem of complex environment dynamic change, the traditional A* algorithm is difficult to apply, so some scholars improve the A* algorithm based on the D* algorithm, and the typical improved algorithm is the D* algorithm. Ganapathy, Yun and Chen [24] proposed an Enhanced D*Lite algorithm to solve the unsafe path problem caused by traversing sharp obstacles. Stent [25] proposed D* computation for locally updating the track cost graph in batches method, effectively solving the problem of obstacle avoidance.

B. Comparative Analysis of Local Obstacle Avoidance Algorithms

For the local anti-collision algorithm: The obstacle avoidance algorithm based on the guidance law simplifies the obstacle to the obstacle circle model, which reduces the computational complexity [3]; The obstacle avoidance of UAV is controlled by acceleration command, which fully considers the constraints of UAV maneuvering performance and has small track deviation but there is a situation that the guidance law needs to be switched frequently when obstacles appear continuously.

The velocity obstacle method has a good performance in dealing with dynamic obstacles. By solving the collision threat situation faced by the UAV and combining different optimization conditions, the velocity solution of the UAV obstacle avoidance can be obtained, which can deal with multiple obstacles at the same time, but the computational complexity is high and requires a certain amount of computing time [12].

The artificial potential field method has certain advantages in computational complexity and path optimality, but the traditional artificial potential field method will have the problems of local optimum and target unreachable in complex environments. The comparison of obstacle avoidance algorithms based on local anti-collision is shown in Table 2.

Table 2. Comparison of local anti-collision algorithms

Types	Advantages	Disadvantages
The guidance law algorithm	The computational complexity is low.	The guidance law needs to be switched frequently in complex environments with constraints.
Velocity obstacle method	It can deal well with dynamic obstacles.	High computational complexity
Artificial potential field method	The planning speed is fast, and the path optimality is good.	Complex environments have local optima.

The artificial potential field method and velocity obstacle method, there are some slight differences between them, as shown in Table 3.

Table 3. Comparison of methods based on potential field and navigation function.

Types	Object of conflict	Dimension	Types of obstacles
Artificial potential field method	Single-machine/multi-machine	2D / 3D	static/dynamic
Velocity obstacle method	Single/multi-machine	2D	dynamic

C. Analysis of Advantages and Disadvantages of Multi-UAV Formation Obstacle Avoidance

1) Artificial potential field obstacle avoidance algorithm

Table 4. Advantages and disadvantages of artificial potential field algorithm

Advantages	Disadvantages
1. The algorithm is simple and easy to understand. *[19]*	1. It is easy to produce local optimal solutions, resulting in the robot or vehicle trapped in an infinite loop.
2. Able to plan a safe and effective path in a complex environment *[19]*	2. The performance of algorithms in complex environments may not be ideal.
3. It can dynamically update the potential energy field to adapt to real-time changes in robots or vehicles.	3. The construction and update of the potential energy field need to consume large resources.

2) Artificial immune algorithm

After a period of development and improvement, the artificial immune algorithm has some unique pros: firstly, the algorithm is more flexible. Artificial immune algorithm uses some artificially designed strategies, such as cloning and mutation strategies, to make the algorithm more flexible [20].

Secondly, there are more stable algorithms. It can avoid the overfitting problem in biological immune algorithms, thus making the algorithm more stable.

At last, it is easier to implement. An artificial immune algorithm does not need to consider the complex physiological mechanism in the biological immune system, so it is easier to implement.

But along with the pros, there will also be some hidden cons: First, the internal mechanism of the immune clonal selection process in the traditional artificial immune algorithm is not deeply studied, so the stability of the algorithm is greatly affected by the antibody concentration.

Second, the method of randomly generating a population in the algorithm will easily lead to the non-uniform distribution of the value of the number in the solution space, thus increasing the phenomenon of data redundancy. Third, there may be premature convergence and a lack of crossover operations.

3) Obstacle avoidance method using ADS-B system

From the advantages of analysis, the ADS-B system can provide almost real-time aircraft position data for the ground control station, which enhances the safety and effectiveness of air traffic control. Secondly, ADS-B has revolutionized the traditional air traffic control mode, replacing ground radar for air traffic control and improving efficiency [26].

Due to its good real-time performance, it can quickly optimize the flight plan, reduce the conflict with other flights and unrelated airspace, shorten the distance, and achieve the purpose of saving fuel, time, and cost. The third is high reliability-- the ADS-B system is based on the joint research and development of multiple large aircraft companies, with high reliability and safety.

However, the ADS-B system also has some drawbacks. Firstly, it is too dependent on facilities. ADS-B system needs to develop corresponding ground facilities and satellite navigation services to realize aircraft positioning and tracking, which requires huge investment [27]. Furthermore, it is considered a security concern because, like any system that relies on electronic devices, ADS-B can be affected by electromagnetic interference and network attacks.

Although the system has corresponding security measures, there are still certain risks. Besides this, privacy concerns are also problems to some extent. The ADS-B system can track the location and status of the aircraft in real-time, which may raise some privacy concerns. For example, the flight trajectory of some flights is a state secret, and public information may reveal sensitive interfaces of this information.

IV. Conclusion

Based on the functions and shortcomings of current obstacle avoidance algorithms, three possible research directions of obstacle avoidance methods are introduced in this dissertation.

The existing problem is that firstly, the computational clutter and planning time of the UAV obstacle avoidance algorithm is too much. Second, the obstacle avoidance process of multiple UAVs needs to consider the formation control factor, which makes obstacle avoidance much more difficult than that of a single UAV.

At present, the algorithm rarely considers the possibility of maintaining the formation and changing the formation of the UAV group during the obstacle avoidance process. It is necessary to consider how to reconcile single-frame UAV independence and UAV formation consensus. Finally, to facilitate the solution, the existing UAV formation obstacle avoidance algorithms are more idealized and lack consideration of UAV formation control under environmental changes and special circumstances. Therefore, how to realize the complex influence factors in reality through modeling is also an open problem.

For future development trends, there are the following prospects: First, for the global obstacle avoidance algorithm, the research of 3D route planning methods in complex environments, especially in dense obstacle environments and complex concave obstacle environments, is the future development trend.

Furthermore, the local obstacle avoidance algorithm considers the dynamic performance of the UAV in the algorithm design, so that the output control quantity satisfies the maximum turning angle rate and the maximum available overload. It reduces the calculation time of UAVs when dealing with continuous dynamic obstacles so that the algorithm has better real-time performance. In addition, the combination of global planning and local planning makes the obstacle avoidance method more complete.

With the increase of UAV missions, it will become the norm for multiple UAVs to perform missions together, and more research will turn to UAV formation obstacle avoidance. In the process of formation obstacle avoidance, each UAV can generate an independent obstacle avoidance path to realize formation transformation and information exchange between each other, improve human-computer interaction ability, and reduce collision risk as much as possible.

In this case, using a single UAV obstacle avoidance algorithm has some limitations. So, the operator can combine different algorithms, and can also improve the robot obstacle avoidance algorithm to obtain better optimization results. In addition, the three-dimensional scene of the flight site is constructed by using the information captured by UAVs combined with other scientific and technological means, and the information synchronization is realized during the flight. In this way, the whole flight process of UAVs can be monitored to improve the safety of the flight and the accuracy of obstacle avoidance.

Although many achievements have been made in the research of UAV obstacle avoidance methods, most of them are still in the theoretical research stage. In the future, more consideration should be given to the study of obstacle avoidance engineering and the feasibility of obstacle avoidance algorithms should be tested in real environments.

Conflict of Interest

The author claims that no conflict of interest exists.

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