

Research on the Application of Multi-rotor UAV Formation in the Hydrological Monitoring Field

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Abstract: In the context of the increasing demand for environmental monitoring, multi-rotor UAV formation has gradually become an important tool in hydrology monitoring. In this study, we propose a control algorithm for UAV formation utilizing an enhanced artificial potential field method. The obstacle avoidance problem in a complex environment for UAV formation is resolved by boosting the repulsive function and incorporating virtual target points, consequently strengthening the formation stability. At the same time, the consistency control algorithm is introduced to further optimize the speed oscillation problem during formation obstacle avoidance. Through MATLAB simulation, the proposed methodology demonstrates a markedly superior performance in the domains of path planning and obstacle avoidance when compared to conventional approaches, which proves its effectiveness and feasibility in practical application.

Keywords: Multi-rotor UAV, formation control, hydrology monitoring, artificial potential field method (APF), consistency control algorithm, path planning, obstacle avoidance performance.

1. Introduction

In conjunction with the rapid advancements in science and technology, the utilization of multi-rotor unmanned aerial vehicles (UAVs) within the domain of hydrological monitoring has been progressively escalating, and their flexibility and efficiency show great potential in environmental data collection. However, the payload capacity and endurance of a single UAV are often a key factor limiting its monitoring efficiency in complex terrain and a wide range of environments. In order to solve these problems, multi-rotor UAV formation, as an emerging technical solution, can effectively overcome the limitations of a single UAV through collaborative work, thereby enhancing the efficacy and accuracy of environmental monitoring endeavors.

In multi-rotor UAV formation, UAVs can share tasks through cooperation and information sharing to breeze up the stability and reliability of the whole system. In hydrological monitoring, the stability and data accuracy of UAV formation are very important. Traditional path planning methodologies, such as the artificial potential field method, are extensively utilized owing to their simplistic structure and computationally efficient nature. However, these methods often face the problem of local minima, which makes the UAVs easily get into trouble in complex environments and can seamlessly execute the monitoring task. Especially in the dynamic and complex hydrologic environment, how to guarantee the stable flight of drone formation and the smooth completion of the task has become a crucial challenge that demands a solution.

The aim of this study is to research and develop a novel UAV formation control approach that enhances the stability and obstacle avoidance capabilities of multi-rotor UAVs during hydrological monitoring missions. By improving the application of repulsion function in artificial potential field (APF) method and introducing a virtual target point and consistency control algorithm, the limitations of the conventional method are resolved. The improved repulsion function can effectively alleviate the dilemma of converging to local minima and improve the route-planning ability of

UAVs in complex environments. The introduction of virtual target points can enhance the flexibility and coordination of the formation, while the consistency control algorithm helps to improve the level of cooperation between the UAV in the formation to ensure the stability of the formation and the smooth execution of the task. Through these improvement measures, this paper hopes to provide a more stable and efficient control strategy for UAV formation, so as to refine the precision and reliability of hydrological monitoring. This not only helps to overcome the limitations of existing methods, but also provides theoretical and technical support for the future application of UAVs in more complex environments.

In terms of formation control, LI ZP and XIAN B proposed a robust, distributed formation control approach grounded in a virtual structure, which significantly improves the formation stability and the resilience to interference of multi-rotor UAVs[1]. By constructing a virtual reference structure, the UAVs can work together according to the predetermined formation shape, so as to realize efficient monitoring in complex terrain. Similarly, QIU HX et al. learned from the behavior mechanism of pigeons and proposed an autonomous formation control method for drones, which enhanced the flexibility and robustness of UAV formation by simulating the collective behavior of pigeons, and was suitable for various hydrological monitoring tasks[2].

Regarding the coordination of UAV formation, ZONG Q, Yang Z, et al. reviewed the state of research on cooperative formation flight control for multi-UAV systems and emphasized the importance of formation flight in UAV hydrology monitoring[3, 4]. They pointed out that the key challenge of current formation control technology lies in real-time response and dynamic obstacle avoidance capability in complex environments, which provides a clear direction for follow-up research. On this basis, LOPEZ-GONZALEZ A et al. introduced a multi-robot formation control approach that relies on distance and direction. By precisely controlling the relative distance and Angle between various UAVs, the formation can operate statically and avoid obstacles efficiently, which is of significant importance for enhancing

the reliability of hydrological monitoring[5]. LI L Q et al. studied an adaptive distributed control method to solve the problem of model parameter uncertainty, and applied it to the formation control problem of AUV[6]. In addition, Zhou JK et al. discussed a flight cooperative control strategy based on Lyapunov method, demonstrating the advantages of this control strategy for attitude cooperative control[7]. Path planning is another key area for multi-rotor UAV formation to effectively perform monitoring tasks in complex environments. ZHANG XL et al. researched the utilization of an enhanced ant colony algorithm for robot path planning and demonstrated the advantages of this algorithm in searching the optimal path in complex terrain[8]. This method is also applicable to the route planning of multi-UAV formation, which is helpful to optimize its path selection in hydrological monitoring tasks. Moreover, SANG HQ and others integrated the enhanced A*algorithm with the artificial potential field method to introduce a hybrid path planning algorithm for formations of unmanned surface vehicles[9]. This algorithm can plan the barrier avert path in the complex hydrological circumstances and improve the overall task execution efficiency of the UAV formation. WANG N et al and YANG WL et al respectively proposed hierarchical path planning algorithms using the fuzzy APF method and dynamic window method, and applied them to the route planning of USV and robotic mermaids[10, 11]. Hashem R et al summarized the research progress related to fully moving multi-rotor UAVs over the past decade and systematically derived and quantitatively evaluated their control assignment matrix[12]. These studies provide new ideas and methods for path planning of multi-rotor UAVs formation in the field of hydrology monitoring, and effectively solve the problem of obstacle avoidance and path optimization of multi-rotor UAVs formation in complex environment.

The research on the application of multi-rotor UAVs formation in the field of hydrology monitoring is deepening, covering formation control, path planning, obstacle avoidance mechanism and so on. Through the interactive analysis of the literature, it can be seen that the current research not only innovates the control strategies of multi-UAVs cooperative operation in theory, but also validates the effectiveness of these strategies in practical applications. Future research can be further combined with artificial intelligence technology to ameliorate the autonomous decision-making ability of UAV formations in dynamic and complex environments, so as to promote the wider application of multi-rotor UAVs in the field of hydrological monitoring.

2. Kinematic Modeling of Multi-rotor UAV

To accurately depict the motion state of UAVs, this paper develops a kinematic model for multi-rotor UAVs. This model employs both the ground coordinate system and the drone coordinate system to describe the position, angle, and velocity variables of the UAV respectively, which provides the basis for the subsequent path planning and obstacle avoidance algorithm design. Through dynamic modeling, the mechanical characteristics and control input of UAVs during flight are considered.

In order to make the kinematic modeling of multi-rotor UAVs, it is usually indispensable to consider the following steps and contents. These steps involve mathematical modeling, the use of coordinate systems to describe motion states, the derivation of mechanical equations, and finally simulation modeling.

2.1. Definition of Coordinate System

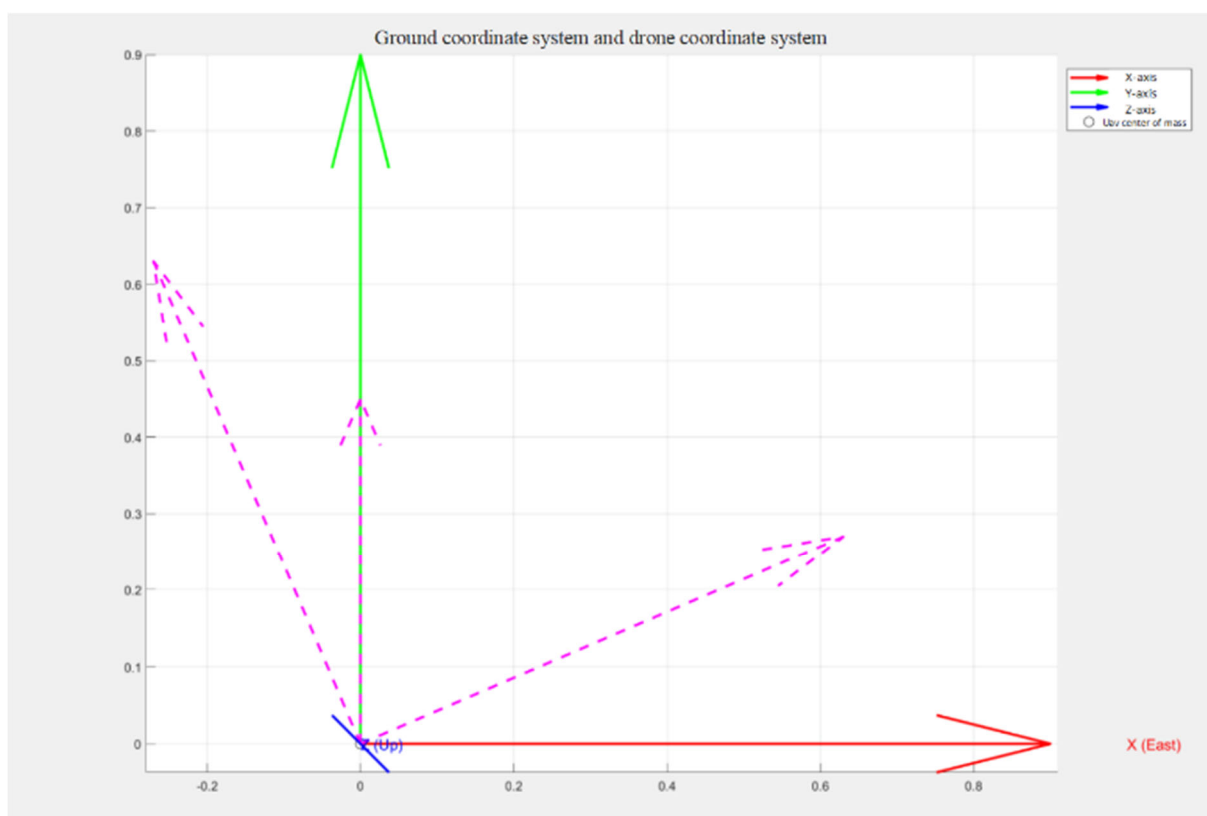


Figure 1. Ground coordinate system and drone coordinate system

The Ground Coordinate System, which serves as a fixed reference, and the Drone Coordinate System, which is attached to the UAV and moves with it, are used to accurately describe the position and orientation of the UAV. Since the flight of the UAV will change its attitude and position, the position and direction of the drone coordinate system relative to the ground coordinate system will constantly change. To convert data such as position, velocity, and attitude between these two coordinate systems, we need to use a rotation matrix. The rotation matrix indicates the rotational relationship between the drone coordinate system and the ground coordinate system[13]. A rotation matrix is a 3x3 matrix that transforms vectors in one coordinate system into another. Let's say a vector in the ground coordinate system is V_g , the corresponding vector in the drone coordinate system is V_b .

Rotation matrix R converts vectors in the ground coordinate system to vectors in the drone coordinate system. This relation can be written as:

$$V_b = R \times V_g$$

If you need to convert a vector in the drone coordinate system back to the ground coordinate system, you can use the transpose of the rotation matrix (i.e., the inverse matrix):

$$V_g = R^T \times V_b$$

Through this rotation matrix, we can accurately transform the motion state of the UAV between different coordinate systems for flight control and navigation.

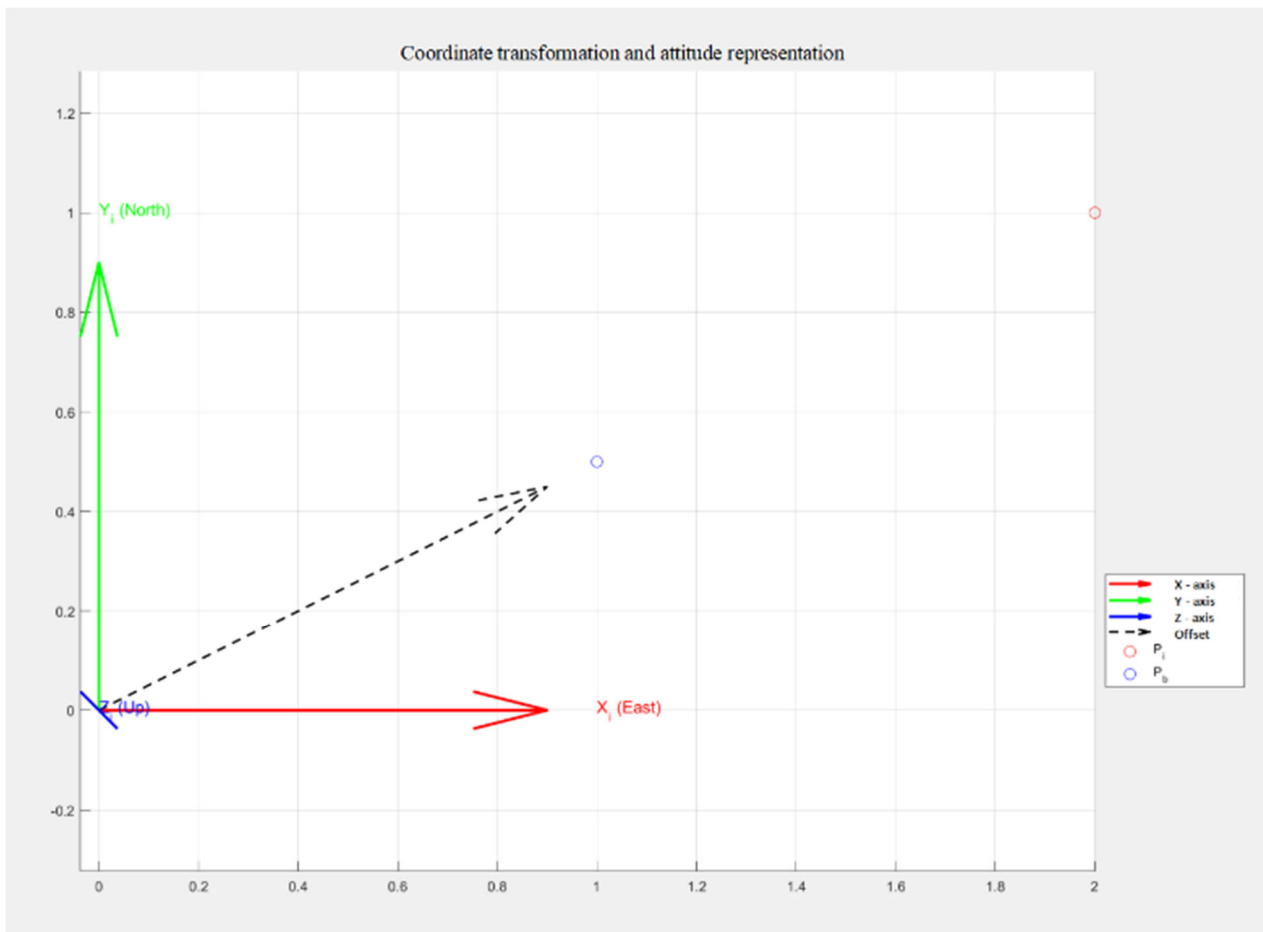


Figure 2. Coordinate transformation and attitude representation

Let the location of the UAV in the ground coordinate system be P_g , its position in the drone coordinate system is P_b , where P_b is the offset in the ground coordinate system relative to centroid of the UAV.

The drone's attitude, or its rotation angle, can be described by the rotation matrix R . This rotation matrix relocates vectors from the drone coordinate system to the ground coordinate system.

If we have a vector in the drone coordinate system, by using the rotation matrix, we can transform it into the ground coordinate system. This transformation relationship can be

expressed as:

$$V_g = R \times V_b$$

V_g represents a vector in the ground coordinate system, V_b denotes a vector in the drone coordinate system, and R is a rotation matrix describing the attitude. With this rotation matrix, we are able to accurately convert the data in the drone coordinate system of the drone to the ground coordinate system for flight control and navigation.

2.2. UAV position and attitude description

2.2.1. Description of position

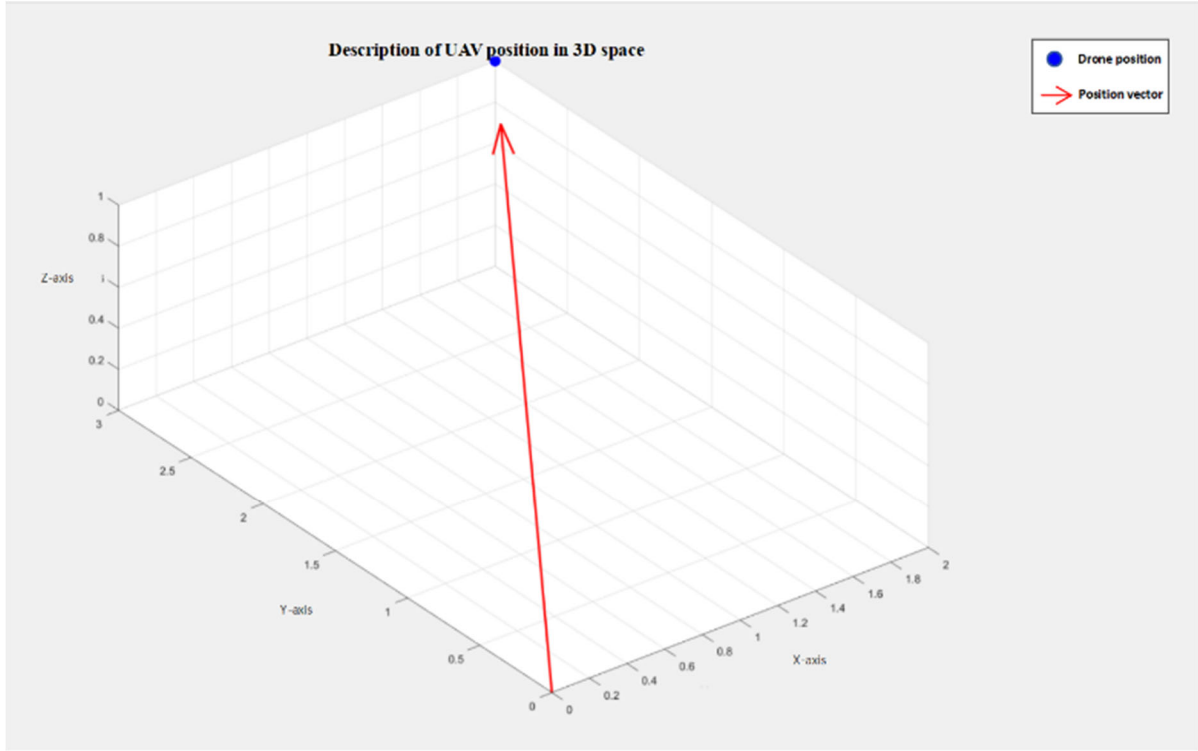


Figure 3. Description of UAV position in 3D space

The position of the UAV in three-dimensional space can be represented by the position vector $p = [x, y, z]^T$ in the ground coordinate system, which indicates its position along the three axes.

2.2.2. Attitude description

The attitude of the drone can be represented by Euler Angle (Roll, Pitch, Yaw) or quaternion. Euler Angle (ϕ, θ, ψ) is used here to describe the rotation Angle of the drone:

1. Roll angle: Denoted by ϕ , it represents rotation around the X-axis.
2. Pitch angle: Denoted by θ , it represents rotation around the Y-axis.
3. Yaw angle: Denoted by ψ , it represents rotation around the Z-axis.

The rotation matrix R, which describes the attitude change, can be expressed as:

$$R = R_z(\psi)R_y(\theta)R_x(\phi)$$

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{bmatrix}, \quad R_y(\theta) = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

$$R_z(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

2.2.3. Derivation of kinetic equations

The dynamics configuration of a multi-rotor UAV is based on the Newton-Euler equation and usually includes the following:

Equation of force:

The force of UAV mainly includes gravity, thrust and air

resistance. Its expression is

$$m \frac{d^2 p}{dt^2} = T + F_g + F_d$$

Among them:

m signifies the mass of the drone.;

$p = [x, y, z]^T$ is the position vector;

T is the thrust vector;

$F_g = [0, 0, -mg]^T$ is the gravity vector;

$F_d = -k_d \frac{dp}{dt}$ stands for the air resistance vector and k_d is the drag coefficient.

Angular dynamic equation

Describes the rotational motion of the drone, given by the Newton-Euler equation:

$$I \frac{d\omega}{dt} + \omega \times (I\omega) = M$$

Among them:

I is the inertia matrix;

$\omega = [p, q, r]^T$ is the vector representing the angular velocities about the x, y, z axes;

$M = [M_x, M_y, M_z]^T$ is the external torque.

3. Improved APF Method

3.1. APF method function

The APF method is a widely use approach in path planning where the goal point generates an attractive force while obstacles crate a repulsive force. The traditional repulsive function causes the drone to converge to a local minimum in some cases, resulting in stagnation. By adding smooth transition function to the repulsion function and setting virtual target point, this paper reduces the problem caused by the rapid growth of repulsion force and ensures that the UAV can smoothly circumnavigate obstacles.

3.1.1. Traditional APF modeling

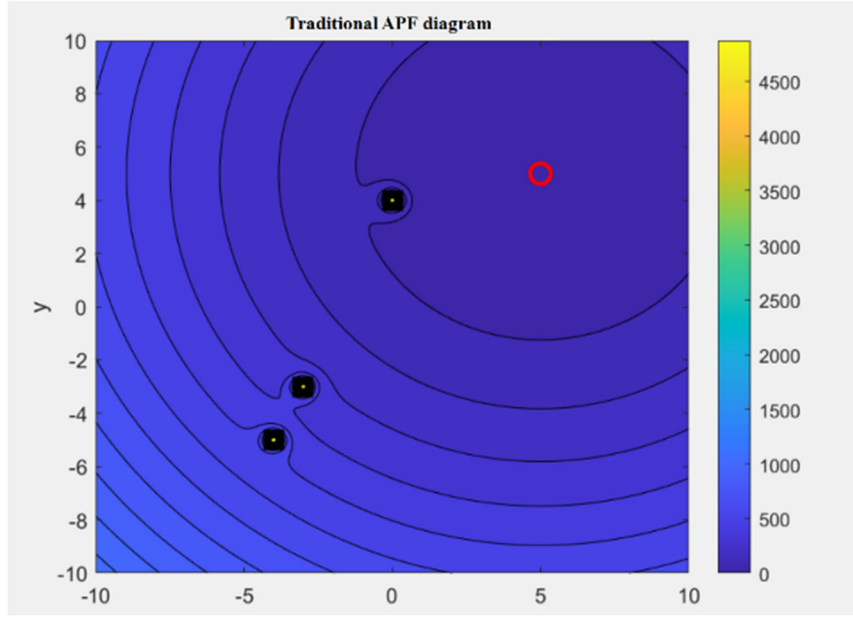


Figure 4. Traditional APF diagram

The traditional APF method models, the attraction of the goal point to the UAV as gravity F_{att} , while the repulsive force exerted by the obstacle on the UAV is represented as repulsive force F_{rep} .

Gravitational potential field model:

$$F_{att} = -\alpha \cdot \frac{r_r - r_p}{\|r_r - r_p\|}$$

In this model, r_r represents the location of the drone, r_p represents the location of the goal point, and α indicates the gravitational coefficient.

Repulsion function model:

$$F_{rep} = \begin{cases} \beta \left(\frac{1}{\|r_r - r_0\|} - \frac{1}{d_0} \right), & \text{if } \|r_r - r_0\| < d_0 \\ 0, & \text{otherwise} \end{cases}$$

In this model, r_0 represents the position of the obstacle, β stands for the repulsion coefficient, d_0 stands for the safe distance.

3.1.2. Improved APF method

To tackle the local minimum problem in the traditional method, an improved APF method is introduced. This method optimizes path planning by setting virtual target points and dynamically adjusting repulsive field.

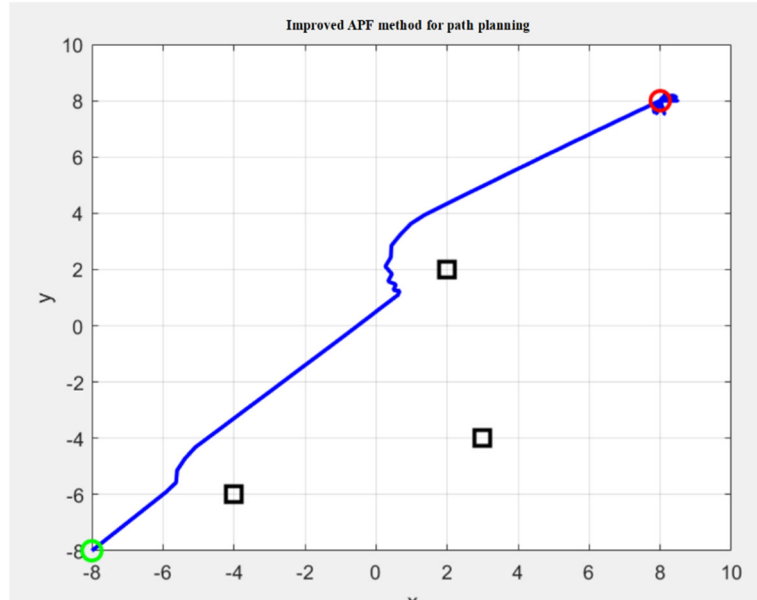


Figure 5. Improved APF method for path planning

Improved gravitational potential field equation model:

$$F_{att}' = \alpha \cdot \left(\frac{r_r - r_p}{\|r_r - r_p\|} + \gamma \cdot \frac{r_r - r_v}{\|r_r - r_v\|} \right)$$

In this model, r_v indicates the virtual goal point and γ is the weight coefficient of the virtual target point.

Revised the model of repulsive force potential field function:

$$F_{rep}' = \begin{cases} \beta \left(\frac{1}{\|r_r - r_0\|^2} - \frac{1}{d_0^2} \right) \frac{r_r - r_0}{\|r_r - r_0\|^4}, & \text{if } \|r_r - r_0\| < d_0 \\ 0, & \text{otherwise} \end{cases}$$

3.2. Introduction of consistency control algorithm

The consistency control algorithm plays a key role in UAV formation control, especially for the speed oscillation problem in formation flight. By introducing this algorithm, the cooperation between UAVs can be enhanced, so that it can show better stability while planning the path and obstacle avoidance. Specifically, the consistency control algorithm balances the relative motion between UAVs by adjusting the control parameters to ensure the overall stability of the formation. Set the relative position between UAVs as x_{ij} , and the consistency control law can be expressed as

$$u_i = - \sum_{j \in N_i} k(x_i - x_j - x_{ij}^*)$$

N_i represents the set of neighbors of the first drone, k is the control gain, and x_{ij}^* is the expected relative position. By adjusting the control gain k , the algorithm can effectively reduce the oscillation amplitude of the speed in the course of obstacle avoidance, and maintain the compact formation and flight stability.

4. PID Control and Simulation

4.1. PID control

To validate the effectiveness of the effectiveness of the consistency control algorithm and the enhanced APF method, PID controller is utilized to precisely adjust the motion of UAV. The introduction of the PID controller enables each UAV to maintain a smooth flight while tracking the target point, avoiding overresponse or lag problems.

The PID control model is as follows:

$$u(t) = k_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

$u(t)$ denotes the output of the PID controller, and $e(t)$ is

the error term, indicating the gap relative to the UAV's current position and the expected position. k_μ , k_i , and k_d are proportional, integral, and differential gains, respectively, through which the controller adjusts the speed and direction of the UAV to accomplish precise path tracking and attitude control.

In the simulation, by adjusting PID parameters, the system response characteristics can be further optimized, so that the UAV formation can still maintain a stable flight state in a complex environment. Specifically, the appropriate proportional gain k_μ can respond to the attitude deviation quickly, the integral gain k_i can eliminate the steady-state error, and the differential gain k_d can restrain the rapid change of error and reduce the phenomenon of overharmonic oscillation. Combined with the consistent control algorithm, PID controller can better coordinate the motion of UAV and improve the stability and obstacle avoidance ability of the whole formation.

4.2. Simulation result

The enhanced APF method is simulated within the MATLAB environment. It is assumed that the UAV operates in a dynamic environment, and both the goal point and the barrier move at a constant speed. Set parameters as follows: Drone speed is $v_r = 0.2$ m/s, drone mass is $m_r = 2.5$ kg, target point mass is $m_p = 2.5lg$, obstacle mass is $m_0 = 0.5lg$, gravitational coefficient is $\alpha = 15$, repulsion coefficient is $\beta = 15$, and PID controller parameter is $K_p = 5, K_i = 0.1, K_d = 0.5$.

Under the same operating environment, both the traditional and the improved APF methods are simulated and verified independently. Set the starting point of drone for (1, 1), target (10, 10), the location of the obstruction, respectively (5.2 8), (3, 6), (3.5 8), (6, 2), (6, 3) and (10, 5).

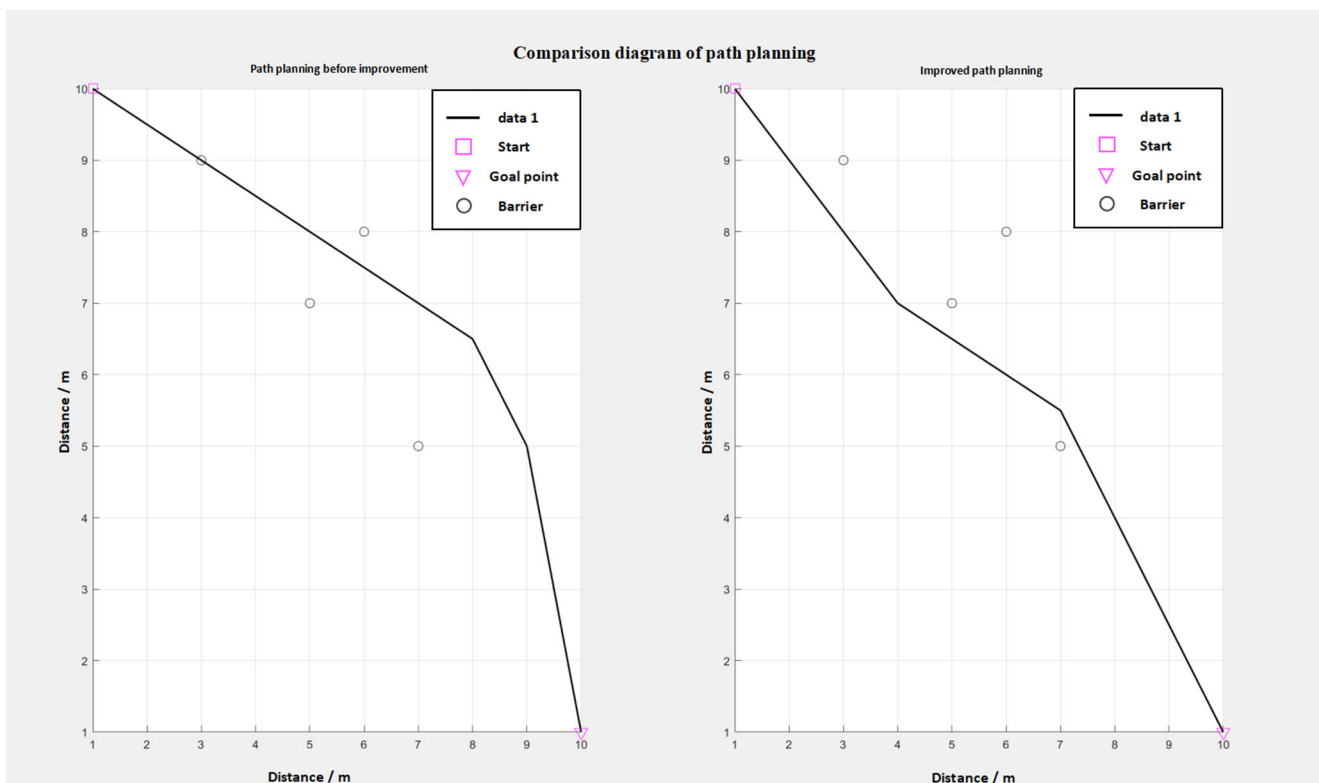


Figure 6. Comparison diagram of path planning

From the simulation results, it is evident that the traditional APF method is easy to be affected by obstacles in the path planning process, especially when obstacles are dense or close to the goal point, the path will show oscillatory behavior, resulting in the final path instability and more detour. The enhanced APF method solves the problem of path oscillation effectively by adjusting the definition of potential field or introducing a new barrier avoidance strategy, to enable the UAV to avoid obstacles more smoothly while sustaining the direction toward the target point. Compared with the traditional method, the improved algorithm is safer and more reliable while maintaining a shorter path, avoiding the possible "local minimum" trap phenomenon.

The enhanced method outperforms the traditional method significantly in obstacle avoidance, path smoothness and computational efficiency, especially in intricate environments, the UAV can swiftly plan a path to evade obstacles and arrive at the goal point. This demonstrates that the improved APF method has great application potential and practical value in the actual application scenarios such as hydrological monitoring.

5. Conclusions

This paper investigates the UAV formation control method utilizing an enhanced APF method and consistency control algorithm, and applies it to the simulation research in the field of hydrological monitoring. Using the conventional path planning method, the repulsive force function with smooth transition and the virtual target point are introduced, which successfully mitigates the local minimum difficulty and enhances the UAV's ability to smoothly avoid obstacles. Concurrently, along with the consistency control algorithm, the possible speed oscillation in the obstacle avoidance process is effectively slowed down, and the steadiness of the UAV formation is further improved.

The simulation outcomes indicate that the enhanced technique exhibits superior route planning and obstacle avoidance capabilities in intricate environments, outperforming conventional methods. In particular, within the domain of hydrology monitoring, formations of multi-rotor UAVs can execute tasks with greater stability and demonstrate heightened adaptability when dealing with environmental perturbations. For future research, efforts could concentrate on refining algorithm parameters further and validating the practicality and dependability of this approach through real-world flight tests. Moreover, integrating additional sophisticated control algorithms with the enhanced APF method could elevate the autonomy and intelligence of UAV formations across a broader range of applications, offering enhanced technological support for hydrological monitoring and beyond.

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