UAV 3D environment obstacle avoidance trajectory planning based on improved artificial potential field method

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Abstract. To address the inefficiency of the traditional artificial potential field method in complex environment for obstacle avoidance, the basic potential field function of the traditional artificial potential field method is improved, and the traditional spherical potential field is proposed to be improved to ellipsoidal potential field, and the improved algorithm is compared and simulated in MATLAB. The results show that the improved artificial potential field method satisfies the UAV to have high efficiency of safety and passability in obstacle avoidance trajectory planning in complex 3D environment.

1. Introduction
Autonomous obstacle avoidance trajectory planning for inspection UAVs is an important component of this problem, which refers to the planning of a collision-free inspection path that avoids various obstacles in an environment of unknown obstacles by the UAV with the help of sensors installed in itself and the feedback it gives, subject to certain constraints. The commonly used obstacle avoidance algorithms are A* algorithm [1], artificial potential field method [2], fast extended random tree method (RRT) [3].

The traditional artificial potential field method with simple mathematical analysis and smooth trajectory is widely used in robot path planning and obstacle avoidance. However, the classical artificial potential field method still has some shortcomings, and in practical applications, dynamic obstacles are also objects to be considered for avoidance by UAVs during flight, making the traditional artificial potential field method unable to meet the obstacle avoidance requirements [4], so some improvements to the method are needed.

2. Traditional artificial potential field method
The artificial potential field method was first proposed by Khatib [5] in 1986 and later improved by P. Khosla [6]. The basic idea is to construct a virtual artificial potential field, a virtual gravitational field is generated from the end target, the direction of which is pointed by the UAV to the end target; a virtual repulsive field is generated around the obstacle, the direction of which is pointed by the obstacle to the UAV, and finally the UAV searches a collision-free trajectory to the end target along the direction of the falling potential field under the superposition of the gravitational and repulsive fields, the UAV in the gravitational and repulsive fields are shown in Figure 1.
Both the gravitational and repulsive functions of the conventional artificial potential field method are related to the distance. The commonly used gravitational field functions are:

\[ U_{\text{grav}}(x) = k_{\text{grav}} (X_u - X_g)^2 \]  

Accordingly, the UAV is subjected to a gravitational force of:

\[ F_{\text{grav}}(x) = -\Delta U_{\text{grav}}(x) \]  

where: \( k_{\text{grav}} \) is the gravitational gain coefficient; \( X_u(x_u, y_u, z_u) \) is the coordinates of the current position of the UAV; \( X_g(x_g, y_g, z_g) \) is the position of the terminal target point; \( X_u - X_g \) is the Euclidean distance between the UAV and the terminal target point.

The common repulsive field function for the combined force is:

\[ U_{\text{rep}}(x) = \begin{cases} k_{\text{rep}} \left( \frac{1}{X_u - X_{\text{obs}}^1} - \frac{1}{X_o} \right)^2, & (X_u - X_{\text{obs}}) < X_o \\ 0, & (X_u - X_{\text{obs}}) \geq X_o \end{cases} \]  

Correspondingly, the repulsive force on the UAV is:

\[ F_{\text{rep}}(x) = -\Delta U_{\text{rep}}(x) \]  

Where: \( k_{\text{rep}} \) is the repulsive force gain coefficient; \( X_{\text{obs}}(x_{\text{obs}}, y_{\text{obs}}, z_{\text{obs}}) \) is the position coordinates of the obstacle; \( X_u - X_{\text{obs}} \) is the Euclidean distance between the UAV and the obstacle; \( X_o \) is the radius of influence of the obstacle.

3. Improvement of artificial potential field method

In order to ensure the efficient passage and safety of the inspection UAV in the complex environment, the traditional spherical repulsive field of the artificial potential field method is improved into an ellipsoidal repulsive field, where the UAV velocity direction and the long semi-axis are always co-linear, and the ellipsoidal size is related to the magnitude of the components of the UAV velocity in the X-axis and Y-axis, and the Z-axis component is equal to the Y-axis component. As shown in Figure 2, the drone is located in the center of the ellipsoid, and the magnitude and direction of its velocity are represented by the vector, the positions of the obstacles are A and B, and the magnitude and direction of their velocities are represented by the vector and respectively. There exists a virtual ellipsoidal repulsive field around the UAV determined by the magnitude of its own motion velocity, and the obstacles located at the edges of the ellipsoidal potential field have different distances to the UAV. Therefore, the improved ellipsoidal repulsive field can give a larger repulsive influence to the obstacles located at high collision possibilities, and the improved repulsive force also decreases with increasing distance as the conventional repulsive force.
The artificial potential field method of elliptical safety area is characterized by the different repulsive forces of obstacles at different locations to the UAV motion, and its advantage is that it can maintain sufficient safety distance for obstacles in the direction of UAV motion, and also improve the UAV’s passability in complex environments. Therefore it is more suitable for application in complex dynamic environments.

The parameters of the ellipsoidal artificial potential field method are related to the velocity of the UAV, and the magnitudes of its long semi-axis $a$ and middle semi-axis $b$ are determined by the components of the UAV’s velocity on the vertical axis $y$, and the horizontal axis $x$, respectively. Cut along the long axis $2a$ of the ellipsoid in any direction, the resulting cross section is shown in Figure 3. From the mathematical principle of the ellipse, the focal length $c_1 = \sqrt{a^2 - b^2}$ can be obtained, and then combined with the UAV’s own coordinates and velocity direction can be derived from the coordinates of the two focal points of the ellipse, as shown in equations (5) and (6).

\[
\begin{align*}
    x_{c1} - x_u &= -\lambda \cdot v_x \\
    y_{c1} - y_u &= -\lambda \cdot v_y \\
    z_{c1} - z_u &= -\lambda \cdot v_z \\
    (x_{c1} - x_u)^2 + (y_{c1} - y_u)^2 + (z_{c1} - z_u)^2 &= a^2 - b^2 \\
\end{align*}
\]

\[
\begin{align*}
    x_{c2} - x_u &= \lambda \cdot v_x \\
    y_{c2} - y_u &= \lambda \cdot v_y \\
    z_{c2} - z_u &= \lambda \cdot v_z \\
    (x_{c2} - x_u)^2 + (y_{c2} - y_u)^2 + (z_{c2} - z_u)^2 &= a^2 - b^2 \\
\end{align*}
\]

where: $(x_u, y_u, z_u)$ are the coordinates of the UAV, and $(x_{c1}, y_{c1}, z_{c1})$ and $(x_{c2}, y_{c2}, z_{c2})$ are the coordinates of the focal $C_1, C_2$ of the ellipse for the cross section, respectively. The condition for
determining the presence of obstacles in the improved potential field requires the geometric definition of the ellipse, and the sum of the distances from the obstacles to the two focal points of the ellipse in spatial coordinates:

\[
d^1 A, C_1, C_2 = \sqrt{(x-x_c1)^2 + (y-y_c1)^2 + (z-z_c1)^2} + \sqrt{(x-x_c2)^2 + (y-y_c2)^2 + (z-z_c2)^2}
\]  

(7)

Considering that the obstacle is of a certain volume and has a range of influence at a certain distance, the above equation is approximated as follows:

\[
d A, C_1, C_2 = d^1 A, C_1, C_2 - 2X_o
\]  

(8)

If \(d A, C_1, C_2 \leq 2a\), the obstacle has the probability of collision with the UAV and requires an obstacle avoidance strategy. Correspondingly, if \(d A, C_1, C_2 > 2a\), so no obstacle avoidance action is needed. For the convenience of calculation, the repulsive function of the improved artificial potential field is defined with reference to the rules of the spherical situation field as shown in Equation (9).

\[
U_{rep} = \begin{cases} 
\frac{1}{2} k_{rep} \left( \frac{1}{d A, C_1, C_2 - 2a} - \frac{1}{X_o} \right)^2, & d A, C_1, C_2 \leq 2a \\
0, & d A, C_1, C_2 > 2a 
\end{cases}
\]  

(9)

Correspondingly, the repulsive force on the UAV is:

\[
F_{rep} = -\Delta U_{rep} = \begin{cases} 
k_{rep} \left( \frac{1}{d A, C_1, C_2 - 2a} - \frac{1}{X_o} \right) \frac{1}{d^2 A, C_1, C_2}, & d A, C_1, C_2 \leq 2a \\
0, & d A, C_1, C_2 > 2a 
\end{cases}
\]  

(10)

Where: \(d x, x_c1, x_c2 \leq 2a\) indicates that the improved repulsive force acts within the virtual ellipsoid, \(F_{rep}\) with the direction pointing from the center of the obstacle to the direction of the UAV.

From the definition of gravitational and repulsive forces, the combined force on the drone can be obtained as:

\[
F_{sus}(x) = \sqrt{[F_{sus}(x)]^2 + [F_{sus}(y)]^2 + [F_{sus}(z)]^2 + [F_{rep}(x)]^2 + [F_{rep}(y)]^2 + [F_{rep}(z)]^2}
\]  

(11)

### 4. UAV autonomous obstacle avoidance trajectory simulation experiment and analysis

The simulation environment is set as a 100m*100m*100m area with six obstacles randomly distributed in the space, and the relevant parameters set in this paper are shown in Table 2 according to the discussion of the parameters of the artificial potential field method in the literature [7]. The simulation results are shown in Fig. 4, Fig. (a) shows the traditional artificial potential field method, and Fig. (b) shows the improved artificial potential field method.

| Table 1 Simulation parameters setting table |
|--------------------------------------------|
| Simulation parameter name            | Value   |
|----------------------------------------|---------|
| Gravitational gain: \(katt\)           | 50      |
| Repulsion gain: \(krep\)               | 1500    |
| Sampling step: \(l0\)                  | 2       |
| Number of cycles: \(t\)                | 500     |
It is obvious from Fig. 4 that the traditional artificial potential field method has a longer obstacle avoidance path when passing the penultimate obstacle, which eventually leads to an increase in the number of trajectory nodes, while the improved artificial potential field method effectively solves this problem. The changes of repulsion and step number during the simulation are shown in Figure 5.

From the first three peaks of Fig. 5, it can be seen that the traditional artificial potential field method has a greater repulsion for UAVs, leading to an increase in the number of nodes of the trajectory planning. The improved artificial potential field method can achieve high efficiency in safety and passability. The total length of the trajectory, the number of nodes and the distance from each trajectory point of the UAV to the target point during the simulation are shown in Table 2 and Fig. 6, respectively.

| Algorithm name                        | Total length/m | Number of nodes |
|---------------------------------------|----------------|-----------------|
| Traditional artificial potential field method | 193            | 95              |
| Improvement of artificial potential field method | 178            | 88              |
5. Conclusions

For the traditional artificial potential field method in the complex environment of obstacles, the inefficient passage and safety problems in path search, the traditional artificial potential field method is improved, the ellipsoidal situation field is proposed, and simulations are performed. The improved algorithm was verified, and the total length of the trajectory was optimized by 7.8% and the number of nodes was reduced by 7.4%, which laid a theoretical foundation for the next research on the trajectory planning of inspection UAVs encountering sudden dynamic obstacles.

References

[1] Zhang, Shuai, Li, X.R., Zhang, P., et al. UAV trajectory planning based on improved A_algorithm_Zhang, Shuai[J]. Flight Mechanics, 2016, 34(3): 39-43.
[2] Wenlin Y,Peng W,Xiaoqi Z, et al. Improved Artificial Potential Field and Dynamic Window Method for Amphibious Robot Fish Path Planning[J]. Applied Sciences, 2021, 11(5).
[3] Jiang ZQ, Ni XH, Wang X, et al. Improved RRT algorithm in UAV trajectory planning[J]. Computer and Digital Engineering, 2019, 47(5): 1131-1135.
[4] Li N,Zhang JH. UAV flight path planning based on improved genetic algorithm[J]. Computer Simulation, 2016, 33(4): 91-94, 170.
[5] Khatib O. Real-time Obstacle Avoidance for Manipulators and Mobile Robots[J]. The International Journal of Robotics Research, 1986, 5(1).
[6] Khosla P,Volpe R. Superquadric Artificial Potentials for Obstacle Avoidance and Approach[C]//Proceedings. 1988 leee International Conference on Robotics and Automation, 1988: 1778-1784.
[7] Ge SS,Cui YJ. New Potential Functions for Mobile Robot Path Planning[J]. Ieee Transactions on Robotics and Automation, 16(5): 615-620.