A SAFETY PROMPT METHOD FOR HELICOPTER FORMATION FLIGHT

Shanxiao & Huang Yang & Lu Chao & Zhou

shanxiao@nuaa.edu.cn njluyang@nuaa.edu.cn zhouchao0113@163.com

Nanjing University of Aeronautics and Astronautics (China)

Abstract

Aiming at the formation maintenance and comprehensive collision avoidance of the helicopter formation under "Leader-follower" mode, a safety prompt method is proposed. This method is based on the artificial potential field method to maintain formation and prevent collision of terrain and other formation members, which prompts helicopter to perform compound escape maneuver when it encounters obstacles and deviates from formation. After determining the research method, the safety threshold of formation maintenance and comprehensive collision avoidance during helicopter formation flying is discussed. Finally, the correctness of the method is verified by numerical simulation.

1. INTRODUCTION

For military helicopters, when a single helicopter performs its mission, it is easy to have problems such as limited vision and attack range, which can be effectively made up by helicopter formation. Helicopter formation refers to the flight of two or more helicopters to maintain formation according to specified intervals, intersection angles and altitude intercepts. Compared with the formation of fixed-wing aircraft, the interval of helicopter formation is closer, and the actual flight environment is more complex, which causes the real position of the helicopter is easier to deviate from the reference position of formation. The helicopter is prone to collision when the interval is too close, and the helicopter is prone to fall behind when it is too far[1]~[3].

In helicopter's airborne equipment, CDTI (Cockpit Display Traffic Information) and ADS-B (Automatic Dependent Surveillance - Broadcast) system can provide traffic situation information in a certain range of airspace centered on the helicopter and the position information of other helicopters in the formation. HTAWS (Helicopter Terrain Awareness Warning System) and HTCAS (Helicopter Traffic Collision Avoidance System) can evaluate the surrounding security situation and direct pilots to avoid collision. However, for helicopters in the formation, the interval is far smaller than the warning threshold set by HTCAS, and they must fly along a certain airspace for a long time according to the specified interval. If the traditional HTCAS is applied in helicopter formation, the false alarm rate will be high [4]~[8].

Therefore, aiming at the flight characteristics of helicopter formation under "Leader-follower" mode[9], this paper proposes a safety prompt method which takes formation maintenance and collision avoidance into account comprehensively. Based on this method, the safety threshold of formation maintenance and collision avoidance is determined. The simulation of formation maintenance and collision warning based on artificial potential field method[10]~[13] is carried out by using MATLAB, and the verification of the method is performed.

2. FORMATION MAINTENANCE

This part mainly discusses the method of helicopter formation maintenance and the calculation method of safety threshold.

2.1. Research Method

In the formation of helicopters, in order to ensure the integrity of the formation, there must be a formation adjustment mechanism, which means

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

there must be a reference point in the formation. Different helicopters are located at different positions of the reference point, so as to form a certain formation.

Formation maintenance control can be done in two steps: firstly, the position of the whole formation is detected and the correct position of the helicopter in the formation is determined based on the current environmental information; and then, it generates an alarm to prompt helicopter to keep position, depending on the helicopter's position deviation.

There are three main ways to choose reference points:

(a) Leader for reference

Choose one leader from a number of helicopters. All other helicopters follow this 'leader' and use the leader's location information to determine their position in the target formation.

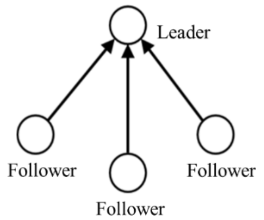

Figure 1 Schematic diagram of leader for reference

(b) Center point for reference

Firstly, sensors are used to sense the position of all helicopters around. Then calculate the central position of all helicopter positions, and use this central position as a reference point to determine the position of each helicopter in the target formation.

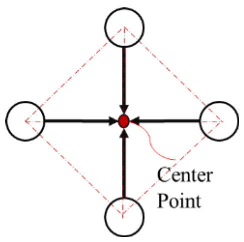

Figure 2 Schematic diagram of center point for reference

(c) Neighboring points for reference

Each helicopter is a reference point with its neighbors, and its position in the target formation is determined by neighbor's position.

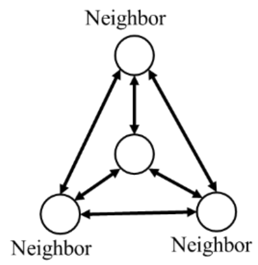

Figure 3 Schematic diagram of neighboring points for reference

As the Leader for reference method only needs to maintain the same relative attitude and velocity with the leader, it can ensure formation maintenance regardless of formation constraints.

The formation in this paper adopts the flight mode of "Leader-follower". The helicopters of formation are divided into two complementary roles: leader and followers, leader decided route, followers at a certain position and angle to track the leader to maintain formation. In the process of formation maintenance, the followers as much as possible to keep their relative position in order to make the system as a whole to achieve optimal performance.

The advantage of this method is that the behavior of the entire formation group can be controlled by only giving the maneuver or trajectory of the leader, the algorithm is simple and efficient, and the feedback speed is fast.

The formation keeping center of each follower are determined according to the actual position of the leader and the basic parameters of formation, which the position deviation of the follower is judged based on. Considering the limited accuracy of navigation and positioning, the follower flying needs to be limited to a certain formation keeping area. Referring to the protective airspace of HTCAS, the formation keeping area of formation helicopters can be set as a cylinder. When the follower deviates from the area, the formation keeping warning will be alarmed. The schematic diagram is shown in Figure 4.

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

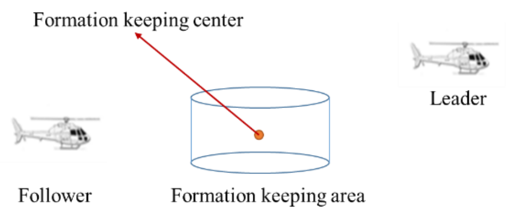

Figure 4 Schematic diagram of formation maintenance method

2.2. Safety Threshold

Based on the methods above, the safety threshold of formation maintenance can be determined by analyzing the relative motion between two adjacent helicopters and characteristic size of the formation. The discussion of the threshold of the formation keeping area includes the height and radius.

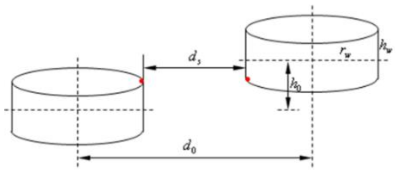

Figure 5 Schematic diagram of formation maintenance safety threshold

According to the vertical collision analysis of two adjacent helicopters, the height of the area can be determined. As shown in Figure 5, the two adjacent helicopters are located in their own keeping areas, and the red dot position in the figure is the most dangerous situation. The height of the keeping area, as the height of the cylinder, is tentatively determined, which is 0.5 times than the predetermined height difference between the two adjacent helicopters in the formation. The vertical safety threshold can be expressed as

$$h_w = 0.5 h_0 \tag{1}$$

where h_0 represents the predetermined vertical distance between the two adjacent helicopters in the formation.

According to the longitudinal collision analysis, the radius of the keeping area can be determined. As shown in Figure 5, assuming that the reason for the longitudinal alarm is that the rear helicopter is faster than the front one, and the escape maneuver is to decelerate to the same speed as the front helicopter, the distance of escape process should include the advancing distance in the reaction time and the deceleration time.

The flight distance of the helicopter during uniform deceleration can be expressed as

$$s = \frac{1}{2} a t^2 \tag{2}$$

where s is the distance of deceleration during which forward speed reduced to zero, a is the acceleration of deceleration, and t is the time taken by the process. Then if we regard ΔV as the ground speed difference of the two adjacent helicopters, we can get

$$s = \frac{(\Delta V)^2}{2a} \tag{3}$$

Assuming that the helicopter keeps its nose up at a pitch angle of α during deceleration, the advancing distance of the escape process can be expressed as

$$d_{s0} = \frac{(\Delta V)^2}{2g \tan\alpha} + \Delta V \times T \tag{4}$$

where g is acceleration constant of gravity, α is pitch angle of fuselage, and T is predetermined pilot reaction time.

By considering a safety factor k, the distance between two keeping areas is finally obtained as

$$d_s = k\left(\frac{(\Delta V)^2}{2g \tan\alpha} + \Delta V \times T\right) \tag{5}$$

Based on the analysis of Figure 5, the radius of the keeping area can be expressed as

$$r_w = \frac{1}{2}\left[d_0 - k\left(\frac{(\Delta V)^2}{2g \tan\alpha} + \Delta V \times T\right) \right] \tag{6}$$

where d_0 represents the predetermined longitudinal distance between two adjacent helicopters in the formation.

Accordingly, the formation maintenance safety threshold of the helicopters, mainly for the followers, are determined during the formation flight. On this basis, the leader monitors followers in the formation whether they exceed the warning boundary in real time. If the warning boundary is triggered, the risk of flight conflict may increase to unacceptable level and it should be used to alert pilots to keep formation.

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

3. COMPREHENSIVE COLLISION AVOIDANCE

This part mainly discusses the method of helicopter formation comprehensive collision avoidance and determined safety threshold of ground collision avoidance and collision avoidance between two helicopters.

3.1. Research Method

In this paper, the forward-looking warning boundary of HTAWS is used as the safety threshold for ground collision avoidance, as is shown in Figure 6. In the course of helicopter flying, the flight trajectory of helicopter is calculated in time at a certain frequency, on the basis of which the forward-looking warning boundary of helicopter is calculated. Then the boundary is compared with the terrain data in topographic database, if the current warning boundary intersects with terrain, the system will give the ground collision alarm. The boundary is regarded as the safety threshold of ground collision avoidance.

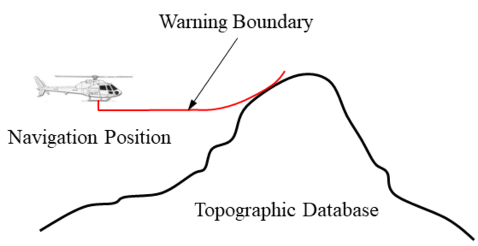

Figure 6 Schematic diagram of safety threshold for ground collision avoidance

Collision between helicopters is mainly avoided by maintaining formation. So the formation maintenance safety threshold of the helicopters can be regarded as the safety threshold of collision avoidance between helicopters.

If formation maintenance and ground collision avoidance alarms are triggered at the same time, artificial potential energy field method is used for compound escape maneuver.

In this paper, attractive potential field is applied to the formation keeping center and repulsive potential field is applied to the obstacle, then the artificial potential energy function is constructed to complete path planning by solving the minimum point. The force diagram of the follower under the artificial potential field is shown in the Figure 7, where represents the attractive force of the formation keeping center and stands for the repulsive force of the obstacle.

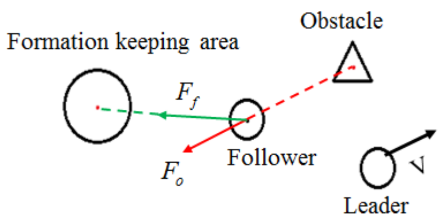

Figure 7 Force diagram of formation members based on artificial potential field method

One of the most important steps in the method of artificial potential energy field is to construct the artificial potential function. Here is the potential function used in this paper.

(a) attractive potential field function

$$U_f = \frac{1}{2} k_f \rho^m (q, q_c) \quad (7)$$

where k_f is attractive force scaling factor, which is positive; $\rho(q, q_c) = q_c - q$ is the distance between the helicopter and the keeping center of formation, where =1 or 2.When you take 1, the gravitational field is parabolic, and when you take 2, it's conic.

The corresponding magnitude of attractive force can be expressed by the negative gradient of the gravitational potential field as

$$F_f(q) = -\nabla U_f(q) = k_f (q_c - q) \quad (8)$$

(b) repulsive potential field function

$$Uo(q) = \begin{cases} \frac{1}{2} k_o \left(\frac{1}{\rho(q,q_o)} - \frac{1}{\rho_0}\right)^2 & \rho(q,q_o) < \rho_0 \\ 0 & \rho(q,q_o) \geq \rho_0 \end{cases} \quad (9)$$

where k_o Is the repulsive force scaling factor, which is also positive; $\rho(q, q_o) = q - q_o$ refers to the distance between the helicopter and obstacle ; ρ_0 is the influence radius of the obstacle. When $\rho(q, q_o)$ is greater than ρ_0 , the obstacle will have no repulsive effect on the formation members.

If we take negative gradient as attractive force, we can get repulsion function

$$F_o(q) = -\nabla U_o(q) = \begin{cases} k_o \left(\frac{1}{\rho(q,q_o)} - \frac{1}{\rho_0}\right) \frac{\nabla \rho(q,q_o)}{\rho^2(q,q_o)} & \rho(q,q_o) < \rho_0 \\ 0 & \rho(q,q_o) \geq \rho_0 \end{cases} \quad (10)$$

The helicopter of formation moves under the combined force of attractive force and repulsion, which can be expressed as

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

(11) $$F_{total} = F_f + F_o$$

3.2. Safety Threshold

In view of the previous section has mainly introduced the method of determining the safety threshold of formation maintenance, the determination of the safety threshold of helicopter collision avoidance is mainly introduced here.

The ground, which can be seen as an obstacle in this paper, affects helicopters in the formation over a certain range. When the helicopter's forward warning boundary intersects with the terrain, the warning is generated and the pilot is prompted to take action. The study of HTAWS forward looking warning boundary, can be divided into longitudinal and lateral warning boundary study.

Firstly we discuss longitudinal warning boundaries, which are mainly based on helicopter escape trajectory obtained by using precise helicopter flight dynamics model.

There should be set aside a safe distance above ground, which is called as the minimum safe height (ΔH). According to the requirements of the TSO-194C minimum safe height can be set to $150m$, but during taking off or landing phase, helicopter flies in low airspace, which is easily to cause false alarm. The minimum safe height is related to helicopter speed, landing gear configuration and the distance from the nearest runway to solve this problem. When the helicopter landing gear is retracted, the minimum safe height varies with the distance of the helicopter to the nearest runway. When the helicopter landing gear is lowered or fixed, the minimum safe height varies with the speed of the helicopter. The schematic diagram of minimum safety height is given in Figure 8 .

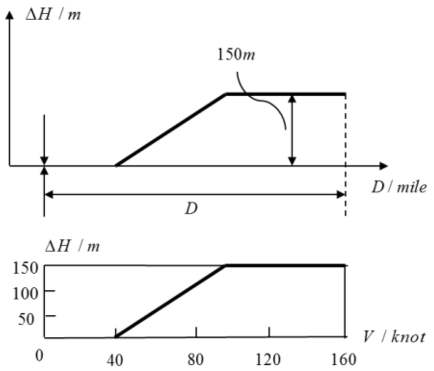

Figure 8 Schematic diagram of minimum safety height

The minimum safe height is designed to offset the helicopter escape trajectory down by a certain distance, leaving a certain safety margin for the helicopter to escape. Figure 9 shows the schematic diagram of longitudinal boundary. In addition, when the helicopter flies over the ridge at a low altitude, additional boundary clipping is required to avoid false alarms.

As mentioned above, the position of the helicopter in the flight process has certain lateral uncertainty, so the warning boundary should have a certain width. Figure 9 shows the schematic diagram of lateral boundary. The initial width of the warning boundary can be set manually as required, for example, to $60m$. The center line extends in the direction of the escape trajectory. The final lateral boundary can be obtained by taking the center line as the reference and extending forward with a certain deviation angle ξ . The boundary width, L at a certain distance in front of the helicopter, x ,can be expressed as

(7) $$L = L_0 + 2x \tan \xi$$

The longitudinal boundary and the lateral boundary constitute the forward - looking warning boundary, just as follow diagram shows.

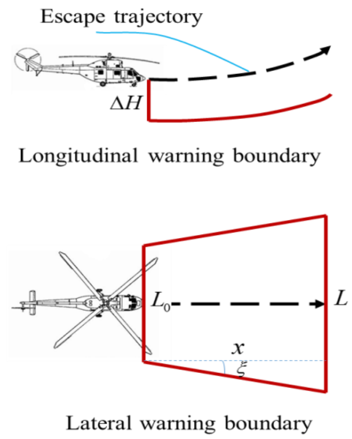

Figure 9 Schematic diagram of forward - looking warning boundary

4. NUMERICAL EXAMPLE SIMULATION

A numerical example is simulated by MATLAB to verify the correctness of the proposed method. Following is a description of the scene settings for the numerical example simulation in this paper. "Leader-follower" mode is adopted by the V-shaped formation, of which the number of leaders

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

is 1 and followers is 4. The followers have all deviated from the formation. The location relationship between the leader and followers are shown in Figure 10.

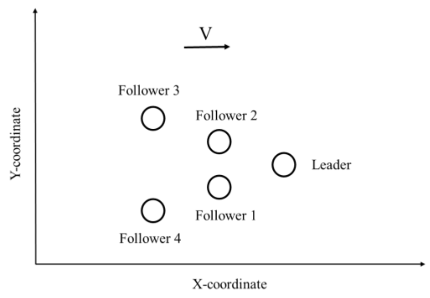

Figure 10 Horizontal plane projection of leader and followers' location

The leader flies higher than followers, the leader moves horizontally and uniformly along the X-axis. The initial speed of the leader is the same as that of followers. According to the leader flying track and the basic parameters of formation, the followers' theoretical flying track points are automatically generated. For research convenience, a rectangular coordinate system of flight horizontal plane is established, which takes the north as the Y-axis positive direction and the East as the X-axis positive direction. The coordinate origin is fixed, and the maneuverability of the followers are sufficient to support all kinds of fast-changing steering flight.

Based on the simulation scene, the formation flying track without or with obstacles are simulated, which are shown in Figure 12 When the formation flying into the obstacle impact area, based on the formation collision avoidance algorithm proposed in this paper, the flying path of followers will deviate, and the final results show that the formation as a whole has achieved successful obstacle avoidance.

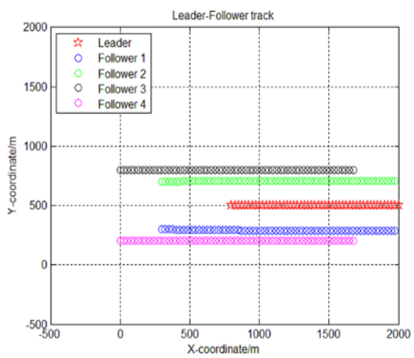

Figure 11 Horizontal plane projection of formation flight track without obstacles

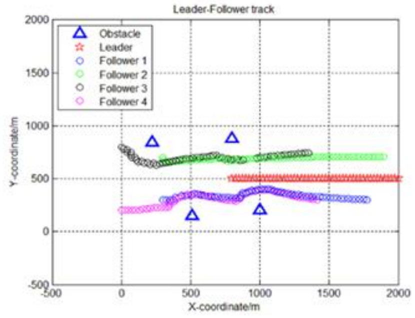

Figure 12 Horizontal plane projection of formation flight track with obstacles

After getting rid of obstacles, the formation members return to the formation keeping area after a period of time under the force of the formation keeping center and complete the formation maintenance. The simulation results are shown in Figure 13.

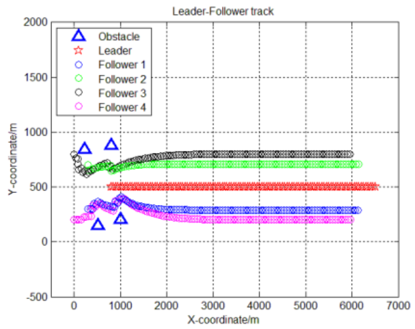

Figure 13 Horizontal plane projection of flight track for formation maintenance

To summarize, the simulation results of this numerical example verify the correctness and feasibility of the safety prompt method mentioned in this paper.

5. CONCLUSION

Aiming at the formation maintenance and comprehensive collision avoidance of the helicopter formation under "Leader-follower" mode, a safety prompt method is proposed. This method is based on the artificial potential field method to maintain formation and prevent collision of terrain and other formation members, which prompts helicopter to perform compound escape maneuver when it encounters obstacles and deviates from formation. After determining the research method, the safety threshold of formation maintenance and comprehensive collision avoidance during helicopter formation

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

flying is discussed. Finally, the correctness of the method is verified by numerical simulation.

REFERENCES

[1]. Chung H . Autonomous formation flight of helicopters: Model predictive control approach[J]. Dissertation Abstracts International, Volume: 67-08, Section: B, page: 4540.;Advisers: S. Shankar Sa, 2006.

[2]. Saffarian M, Fahimi F. A Novel Leader-Follower Framework for Control of Helicopter Formation[C]// Aerospace Conference. 2007.

[3]. ALBERT WU.JONATHAN P-HOW. Guaranteed infinite horizon avoidance of unpredictable, dynamically constrained obstacles[J]. Auto Robot, 2012, 32:227-242.

[4]. Zhou Chengzhong, Lu Yang. Research on helicopter forward looking terrain warning algorithm [J]. Flight mechanics, 2016(3):30-33.

[5]. Liu Yifen. Research on simulation and verification platform of helicopter ground proximity warning [D].

[6]. Chen Guangyong. Research on alarm curve algorithm model and control simulation of ground proximity warning system [D]. Nanjing university of aeronautics and astronautics, 2008.

[7]. Livadas C , Lygeros J , Lynch N A . High-level modeling and analysis of the traffic alert and collision avoidance system (TCAS)[J]. Proceedings of the IEEE, 2000, 88(7):926-948.

[8]. Zhao Xin. Research on integrated system of air collision prevention and ground proximity warning [D]. Nanjing university of aeronautics and astronautics, 2012.

[9]. Consolini L, Fabio Morbidi, Domenico Prattichizzo, et al. Leader–follower formation control of nonholonomic mobile robots with input constraints[J]. Automatica, 2008, 44(5):1343-1349.

[10]. Paul T , Krogstad T R , Gravdahl J T . Modelling of UAV formation flight using 3D potential field[J]. Simulation Modelling Practice & Theory, 2008, 16(9):1453-1462.

[11]. Ge S S , Cui Y J . Dynamic Motion Planning for Mobile Robots Using Potential Field Method[J]. Autonomous Robots, 2002, 13(3):207-222.

[12]. Koren Y , Borenstein J . Potential field methods and their inherent limitations for mobile robot navigation[C]// Proceedings. 1991 IEEE International Conference on Robotics and Automation. IEEE, 2002.

[13]. Ding Jiaru, Du Changping, Zhao Yao, et al. Uav path planning algorithm based on improved artificial potential field method [J]. Computer applications, 2016, 36(1):287-290.

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019