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A Novel Collision Avoidance Method for Fixed-wing Unmanned Aerial Vehicles

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Abstract: In this paper, we study collision avoidance problems with fixed-wing unmanned aerial vehicles (UAVs). According to the spatial position and relative speed between the UAVs, several sufficient conditions for avoiding collisions are proposed. An emergency control algorithm is designed based on the sufficient conditions to ensure that the UAVs can be driven from a dangerous state to the safe area. In order to prevent frequent switching of states of the UAV between "safe mode" and "danger mode", a conflict buffer is additionally introduced for conflict resolution and smooth transition. The sufficient conditions can not only be applied to the collision avoidance problem with static and dynamic obstacles, but also can be directly extended to the internal collision avoidance between multiple vehicles. Meanwhile, control input saturation is explicitly considered for the emergency maneuver. Simulations are presented to illustrate effectiveness of the proposed algorithm.

Key Words: fixed-wing UAVs, collision avoidance, sufficient conditions, conflict buffer

1 Introduction

Due to its small size, low cost and compact structure, small unmanned aerial vehicles (UAVs) have a host of scientific and commercial applications [1]. In particular, UAV swarm or formation flight are a hot issue that has been studied recently. One of the most basic conditions in formation control is to verify that each sub-vehicle can fly safely without collision [2]. The problem of collision avoidance was first proposed for conflict resolution in the route management of civil aviation aircraft, and the effective flight path was planned by using the collision cone model of the aircraft and the relative speed of the vehicles [3].

With the advent of UAV, research on the problem of collision avoidance of UAVs is developing at an unprecedented rate. A multitude of problems related to collision avoidance control of fixed-wing UAVs (including limited turning rate, high speed cruise, subject to wind disturbance) have been studied extensively recently [4][5]. The approaches addressed in the papers can be easily divided into two categories:

Planning- the purpose is to enable the UAV to plan a non-conflicting desired path in advance in the space, and the path can also be updated online in real time. Planning-based approach will be confronted with a challenge to design a suitable collision avoidance path when the UAV has control constraints, since it is difficult for UAVs to remain above the desired path all the time, as described in [7]. In order to overcome this problem, many path planning methods based on real-time optimization theory are proposed for online correction of the desired path [8].

Emergency control- Due to the existence of certain tracking errors, it is difficult to ensure effective collision avoidance by simply using the planning method. When the location of the vehicles are relatively close and may collide, some emergency control strategies are needed to ensure that the vehicle can quickly get rid of the dangerous area and return to the appropriate path.

The UAV is affected by the environment (intrusion of moving targets and other vehicles, etc.) and its own motion characteristics (wind disturbance and control performance, etc.) [6]. There must be certain tracking errors, and it cannot move completely according to the predetermined trajectory. However, the definition of the long-period desired trajectory can provide the expected response for the collision avoidance of the UAVs and realize the smooth realization of the evasive action. The reaction control formula makes a real-time control response based on the intruder information. This action can be directly corresponding to the actuator, with fast response, short cycle, simple and effective.

Most research on collision avoidance issues has focused on planning-based approaches, and the approach to emergency control has drew relatively little attention in the article. The planning method is mainly to use optimization theory or continuous online update of waypoints or routes to result in no collision, for example, decentralized model predictive control (MPC) and consensus-based control are proposed for a multi-UAV system collision avoidance[11]. The problem of collision avoidance is regarded as coupled constraints in the optimization of MPC. A dual-mode control approach is developed to calculate the required control output online. "Danger mode" is always present, only activates and dominates the control of the vehicle in the presence of possible collisions, and at other times is the "safe model" work [14]. This work is limited because there is an additional smooth transition between the control outputs of the two modes, which is often a nontrivial task. Reachable sets are employed to tackle the moving collision avoidance problem in a cooperative mission. The motion uncertainty is performed with reachable sets and a real-time path planning algorithm is proposed [10]. A method based on waypoint sampling and pagating a flight path steming from the start, desired path is generated and checked against the states of the UAV and intruded obstacle aircraft online [12].

The research motivation of the emergency control methods stems from the safety (or conflict) regions and dynamical systems of the UAVs. A collision avoidance system using fuzzy steering controller for pedestrian collision avoidance in emergency situations is proposed in [9], which adopting the information data fuzzy training in the low-speed stage, the collision avoidance control output at high speed is obtained. A game theoretic method is introduced to tackle priori bounds and other bounds to generate separation for cooperative vehicles [13]. Control strategies for nonhonlonomic vehicles to safely complete the task while avoiding collisions are proposed in [15]. Similarly, the method is divided into two parts: path tracking with limited input and real-time non-cooperative collision avoidance. However, it is manifest that most of the above articles only consider two-vehicle cooperation or non-cooperative collision avoidance. These methods are difficult to extend to the handling of multi-vehicle internal collision avoidance problems.

As reported in [5], it is imperative that rigorous condition of collision avoidance is needed, i.e., for which it is rigorously ensured that possible collisions will eventually be avoided. This requires that some sufficient conditions be imposed on the control algorithm on the basis of satisfying some basic premise assumptions. To quantitatively investigate the sufficient conditions of collision avoidance of fixed-wing UAVs, we proposed a novel collision avoidance method to implement collision-free emergency maneuver. Inspired by the work of [14], an additional transition phase is introduced for a smooth transition between "safe mode" and "dange mode". The control algorithm proposed in this paper does not consider the situation of two or more vehicles in the initial stage of design, and the sufficient conditions can be extended to the situation of multiple vehicles. Therefore, the algorithm proposed in this paper can directly extend to multi-vehicle collision avoidance.

This paper is organized as follow. In section 2, we describe the regional division of the UAV. The sufficient conditions of collision avoidance is presented in Section 3. Sections 4 and Sections 5 include the control maneuver of the system and results of simulations, respectively.

2 Problem Overview

2.1 Dynamics of fixed-wing UAVs

In order to clearly consider the collision avoidance problems of fixed-wing UAVs in which vehicles fly at constant speed and altitude, i.e., planar motions. The dynamic model of the UAV is presented as [16]

$$\begin{aligned} \dot{x} &= v\cos\psi \\ \dot{y} &= v\sin\psi \\ \dot{\psi} &= \omega \end{aligned} \tag{1}$$

where, x, y represent the planar position of the UAV, v indicates the speed of the UAV, ψ and ω express the heading and the heading rate of the UAV, respectively.

Assume that the flight speed and turning rate of the UAV are bounded, that is to say

$$\begin{gathered} v_{min} \leq v \leq v_{max} \\ \omega_{max} \leq \omega \leq \omega_{max} \end{gathered} \tag{2}$$

where, v_{min}, ω_{max} and v_{max}, ω_{max} represent the upper and lower bounds of v and ω, respectively.

2.2 Definitions of Region

Inspired by the concept of reachable sets and the work in [15], we adopt the following definitions of regions (see Figure 1). We employ d_{ij} to represent the distance between the centroids of any two vehicles i and j.

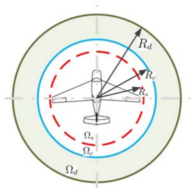


Fig. 1: The definitions of regions

- Detection region Ω_d: The maximum area that the UAV's sensor can detect. R_d represents the distance of detection.

$$\Omega_d = \{d_{ij}, d_{ij} < R_d\} \tag{3}$$

  When the vehicle j is outside of the detection region of the vehicle i, it is not need to consider the possibility of collision avoidance.
- Conflict region Ω_c: In this region, vehicle i and j may collide, but there is a buffer area, the conflict region, enabling the vehicle to perform an emergency collision avoidance algorithm within the buffer area.

$$\Omega_c = \{d_{ij}, R_s < d_{ij} < R_c\} \tag{4}$$

  where, R_c indicates the radius of conflict and is a constant that needs to be defined in advance.
- Safe region Ω_s: A minimum safe area around the vehicle, and the radius of which is usually expressed as $R_s > l_{ws}$, where l_{ws} represents the wingspan of the vehicle.

$$\Omega_s = \{d_{ij}, d_{ij} < R_s\} \tag{5}$$

  Other vehicles or obstacles are prohibited from reaching the safe region throughout the flight.

Inspired by the work of [14], the concepts of "safe mode" and "danger mode" are introduced. We define that there is no possibility of collision when the vehicle j is outside the detection region of the vehicle i. In safe mode, the vehicle performs the desired command of mission operations; in the danger mode, the vehicle employs emergency collision avoidance control operations and shields all mission operations. When the vehicle j is in the detection area and conflict region of the vehicle i, the vehicle j is in safe mode and danger mode with respect to the vehicle i, respectively.

Remark 1 *It is assumed that the position and velocity information between all other UAVs within the detection range of the vehicle i during the entire formation or swarm flight can be transmitted to the vehicle i without delay.*

3 Sufficient Conditions

In the two-dimensional space, the most easily obtained is the position and speed information of the UAVs. If the position of any two vehicles in space are greater than the safe distance R_s, and the relative position is monotonously increasing in the future, obviously the two aircraft will not collide. As shown in figure 2, vector $P_i - P_j$ represents the relative positions of the vehicle i and the vehicle j. $\dot{P}_j$ represents the speed of the vehicle j, if

$$\dot{P}_j(P_i - P_j) > 0 \tag{6}$$

the two vehicles will move farther and farther (see left part of figure 2). Otherwise, if

$$\dot{P}_j(P_i - P_j) < 0 \tag{7}$$

the two vehicles are close to each other, the collision may be caused by a relative distance less than the safe radius (see right part of figure 2).

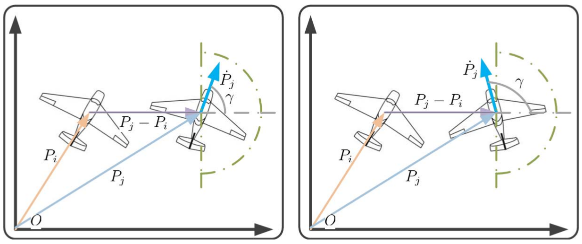


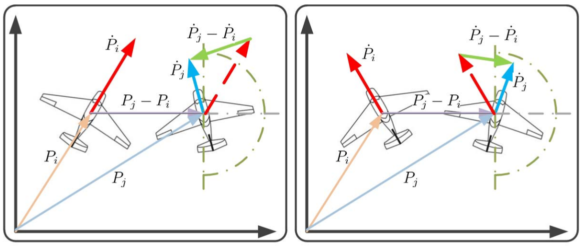
Fig. 2: The most primitive way to avoid collision

In conditions (6) and (7), only the motion of the vehicle j are considered and the motion of the vehicle i is ignored. If the speed of the vehicle i is fast or the motion characteristics are complicated, the conditions (6) and (7) cannot completely guarantee that the vehicles will not collide.

If both the position and speed of the vehicle i and j are considered, we introduced that

$$(\dot{P}_j - \dot{P}_i)(P_j - P_i) > 0 \tag{8}$$

can ensure that the two vehicles are away from each other (as shown in right part of figure 3). Taking vehicle j as the research center, if the relative speed of the two vehickes is gradually approaching the left half of the speed of the vehicle j where the vehicle i is located, as shown in the left half of figure 3, the two vehicles may collide.



$(\dot{P}_j - \dot{P}_i)(P_j - P_i) < 0$ $\quad$ $(\dot{P}_j - \dot{P}_i)(P_j - P_i) > 0$

Fig. 3: Collision avoidance with relative position and velocity vector

Considering the collision cone concept of the UAVs [3], condition (8) can be further refined into theorem 1.

We use $P_i(0), P_j(0)$ and $v_i(0), v_j(0)$ to indicate the position and speed of any two vehicle i and vehicle j in the space at the initial moment. The relative position and relative speed of the two vehicles at the initial moment are expressed as

$$\begin{aligned} P_{ij}(0) &= P_i(0) - P_j(0) \\ v_{ij}(0) &= v_i(0) - v_j(0) \end{aligned} \tag{9}$$

Without any heading control adjustment, the position of the two vehicles after time t is

$$P_i(t) = P_i(0) + \int_0^t v_i dt = P_i(0) + v_i t \tag{10}$$

$$P_j(t) = P_j(0) + \int_0^t v_j dt = P_j(0) + v_j t$$

At this point, the relative distance between the two vehicles is

$$\begin{aligned} P_{ij}(t) &= P_i(t) - P_j(t) \\ &= P_{ij}(0) + (v_i - v_j)t \\ &= P_{ij}(0) + v_{ij}t \end{aligned} \tag{11}$$

Theorem 1 *The sufficient condition that two aircraft do not collide in space is:*

1) $|P_{ij}(0)| \geq \frac{v_i+v_j}{u_{max}} = \frac{2v}{u_{max}}$

2) $R_s \geq \frac{v_i+v_j}{2u_{max}} = \frac{v}{u_{max}}$

3) $|\gamma| \geq \arcsin\frac{2R_s}{P_{ij}(0)} = \beta$

where, u_{max} *represents the maximum heading angular velocity and* γ *represents the angle between the relative speed direction and the initial position of the aircraft.*

Proof: First, we discuss the relationship between the relative position of the two vehicles P_{ij} and the safety radius R_s (see in figure 4). It is assumed that at the initial moment, the relative distance between the two vehicles is greater than 2 times the safe radius, $P_{ij} \geq 2R_s$(if not satisfied, the two aircraft have already collided).

we consider the worst case – the two vehicles are facing each other. Obviously, the two vehicles can avoid collision safely if the safety distance R_s must be greater than the minimum turning radius r_{min}. It is obtained that

$$R_s \geq r_{min} = \frac{v}{u_{max}} \tag{12}$$

Therefore, we can obtain

$$|P_{ij}(0)| \geq 2R_s \geq \frac{2v}{u_{max}} \tag{13}$$

Assume that during the movements of the two vehicles, at time t^*, $|P_{ij}|$ reaches a minimum, i.e., $|P_{ij}(t^*)| = \min|P_{ij}(t)|$. We introduce a quadratic minimum,

$$\frac{\partial |P_{ij}(t)|^2}{\partial t}|_{t=t^*} = 0 \tag{14}$$

to extend that

$$2P_{ij}(t^*)\dot{P}_{ij}(t^*) = 0 \tag{15}$$

According to the formula (11),

$$\dot{P}_{ij}(t^*) = \dot{P}_{ij}(0) + \dot{v}_{ij}t^* + v_{ij} \tag{16}$$

Regardless of changes in the speed of vehicle, that is to say, $\dot{v}_{ij} = 0$. It is manifest that

$$\dot{P}_{ij}(t^*) = v_{ij} \tag{17}$$

Since $P_{ij}(t^*) = P_{ij}(0) + v_{ij}t^*$, both sides of the equation are simultaneously multiplied by v_{ij}^T to get

$$P_{ij}(t^*)v_{ij}^T = P_{ij}(0)v_{ij}^T + v_{ij}v_{ij}^T t^* \tag{18}$$

Combining with (15) and (17) gives

$$t^* = -\frac{P_{ij(0)}v_{ij}^T}{|v_{ij}|^2} \tag{19}$$

In order to ensure that there is no collision between the vehicles, it is necessary to ensure that the minimum distance between the two vehicles is always greater than 2 times the safety distance R_s.

$$\min |P_{ij}(t)| = |P_{ij}(t^*)| \geq 2R_s \tag{20}$$

Calculating $|p_{ij}(t^*)|$ directly,

$$\begin{aligned} |P_{ij}(t^*)| &= \sqrt{P_{ij}(t^*)P_{ij}^T(t^*)} \\ &= \sqrt{P_{ij}(t^*)(P_{ij}(0)+v_{ij}t^*)^T} \\ &= \sqrt{P_{ij}(t^*)P_{ij}^T(0)+P_{ij}(t^*)v_{ij}^T t^*} \\ &= \sqrt{(P_{ij}(0)+v_{ij}t^*)P_{ij}^T(0)} \\ &= \sqrt{|P_{ij}(0)|^2 - \frac{|v_{ij}P_{ij}^T(0)|^2}{|v_{ij}|^2}} \\ &= |P_{ij}(0)||\sin\gamma| \end{aligned} \tag{21}$$

Since γ is defined as the angle between the relative velocity and the initial position vector, $\gamma \in [0, \pi]$. So we can finally obtain that

$$|\gamma| \geq \arcsin \frac{2R_s}{P_{ij}(0)} = \beta \tag{22}$$

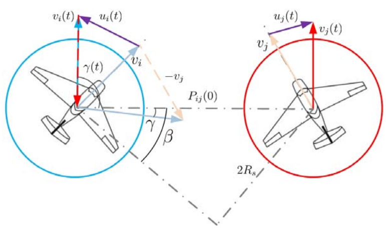


Fig. 4: Relative position and velocity vector

Remark 2 *Once any two vehicles meet the sufficient conditions in Theorem 1, there will be no collisions in the future. There is no need to consider collision avoidance operations. If we can ensure that the performs of vehicles certain collision avoidance operations in conflict with each other, so that the sufficient conditions in the Theorem 1 are satisfied to avoid collision.*

4 Control Scheme

The objective of the control scheme is to ensure that the vehicle can make deconfliction maneuvers based on the adequate conditions given previously. Meanwhile, the smooth transition between safe mode and danger mode and the collision avoidance operation in the case of multiple vehicles also need to be considered.

4.1 Deconfliction Maneuver

The operation of emergency collision avoidance should ensure that the vehicles gradually increases in relative distance during the next movement and satisfies the non-collision sufficient conditions in Theorem 1.

Theorem 2 *For a planar n-vehicle system, it is assumed that the vehicles in the system are flying at a constant speed v. There is no conflict between all the vehicles at the initial moment. If there is a conflict between any two of the vehicles, then the collision avoidance operation (heading adjustment) is designed as*

$$u = \pi/4 + \rho \arccos \frac{v_{ij}P_{ij}(0)}{|v_{ij}||P_{ij}(0)|}, \rho = \pm 1 \tag{23}$$

to ensure that the two vehicles effectively avoid collisions.

Proof: For a n-vehicle system, we choose two of them, vehicle i and j to design a collision avoidance control strategy. Assume that there is no collision conflict between the two vehicles at the initial moment, $P_{ij}(0) \geq 2R_s$. It is manifest that

$$\beta = \arcsin \frac{2R_s}{P_{ij}(0)} \leq \pi/2 \tag{24}$$

At the same time, it is assumed that the selection of the safety distance, R_s, satisfies the non-conflict sufficient condition

$$R_s \geq \frac{v_i + v_j}{2u_{max}} = \frac{v}{u_{max}} \tag{25}$$

$\psi_i(0)$ and $\psi_j(0)$ respectively represent the initial heading angles of the two vehicles, and u_i and u_j indicate the avoidance operations of the two vehicles, respectively.

In order to avoid collisions, the heading adjustments of u_i and u_j of the two vehicles must have opposite signs, that is, the heading angle of one vehicle increases while the heading angle of the other vehicle must decrease. Therefore, we introduce a direction factor, ρ, in the formula (23).

Without loss of generality, we assume

$$\begin{aligned} u_i &= \pi/4 - \arccos \frac{v_{ij}P_{ij}(0)}{|v_{ij}||P_{ij}(0)|} \\ u_j &= \pi/4 + \arccos \frac{v_{ij}P_{ij}(0)}{|v_{ij}||P_{ij}(0)|} \end{aligned} \tag{26}$$

In a very short time t_u, the amount of change in the position of the vehicles is not large. However, the adjustment of the heading angle can be directly superimposed on the nose of the vehicles. Then the angle γ between the relative position and relative speed of the two vehicles is $\Delta\angle v_{ij}$. Therefore, after the adjustment, the heading angles of the two vehicles are

$$\begin{aligned} \psi_i(t_u) &= \psi_i(0) + u_i \\ \psi_j(t_u) &= \psi_j(0) + u_j \end{aligned} \tag{27}$$

Therefore, the increment of the angle between the relative speeds of the two vehicles can be expressed as

$$\begin{aligned} \Delta\angle v_{ij} &= |\angle v_{ij}(t_u) - \angle v_{ij}(0)| \\ &= |\psi_i(t_u) - \psi_i(0) + (\psi_j(t_u) - \psi_j(0))| \\ &= |u_i + u_j| \\ &= \pi/2 \end{aligned} \tag{28}$$

Combining with (24) gives

$$|\gamma| \geq \beta \tag{29}$$

satisfies the non-conflict sufficient conditions in Theorem 1.

4.2 Smooth Transition

Determining whether the vehicle is in safe mode or danger mode depends on the relationship between the relative distance between the two vehicles and the collision radius R_c. Due to the time-varying position of the vehicle, the relative distance may mutate back and forth between the two cases, which are larger or smaller than the collision radius R_c, resulting in the mode of the vehicle switching back and forth. It is clear that the control output of the vehicle is inconsistent in different modes, which will result in dithering of the control output.

We introduced the concept of conflict buffer to effectively avoid unnecessary switching back and forth between different modes. The conflict buffer means that the conflict radius of the safe mode entering the dangerous mode R_c^i is different from the conflict radius of the dangerous mode to the safe mode R_c^o, and $R_c^o > R_c^i$. The loop between R_c^i and R_c^o is called the conflict buffer.

When the vehicle enters the danger mode from safe mode, the vehicle is still in safe mode when passing through the conflict buffer. The control output does not change. Once the vehicle switches to the danger mode, it is needed to return immediately to the conflict region. The vehicle must pass through the conflict buffer again during the return flight. At this time, the vehicle is still in the danger mode, and the control output does not alter as well.

4.3 Case of Multiple Vehicles

Control strategy (23) gives the collision avoidance operation of any two vehicles in the planar n-vehicle system. Here we introduce an influence coefficient, k_i, which represents the effect of other vehicles within the swarm on the collision avoidance operations of the vehicle.

$$k_i = \frac{(R_c^a - P_{ij})^2}{(R_c^a - R_s)^2} \tag{30}$$

where, R_c^a represents a distance constant designed in advance, and P_{ij} represents the distance between two vehicles that may collide. Then, $0 \le k_i \le 1$, and the total output of the avoidance operations is

$$U = \sum_{i=1}^{n} k_i u_i \tag{31}$$

According to the previously designed control strategy, a summary on the proposed methods is presented as follow.

5 Simulations

To validate the performance of the design control method, a high performance hardware-in-the-loop simulation environment was developed. It is mainly composed of X-plane platform, self-developed flight control system and ground station system [17].

The velocity of the UAV is set as 5 m/s. Wingspan of the UAV is 0.4 m, and weight of the UAV is 1280 g. we designed two sets of simulation experiments.

5.1 Avoidance of static and dynamic obstacles for single UAV

As shown in Figure 5, we choose three static obstacles to be distributed in (2,3),(3,2) and (4.5,5). The UAV (red line) moves from Start point (0,0) to End point (10,10). Meanwhile, two UAVs (blue line and green line) acted as intruders to interfere with the movement of the UAV.

The parameter selection in the algorithm is: $R_d = 3$, $R_c^i = 1.5$, $R_c^o = 2$, $R_s = 1$, $R_c^a = 1.7$. The trajectory of the UAV is shown in Figure 5. Figure 5(A) shows the trajectory of the UAV from time 0 to time 1 s. It can be seen that the distance between the UAV and the dynamic obstacle is relatively long, and the distance from the static obstacle is relatively close. Therefore, avoidance actions are based on static obstacles. Figures 5(B) and (C) show the trajectories of the UAV from time 1s to 1.5s and from 1.5s to 2.2s, respectively. Figure 5(D) shows the last trajectory of the UAV. It can be seen from the figure that the UAV has better avoidance performance for both static obstacles and dynamic obstacles.

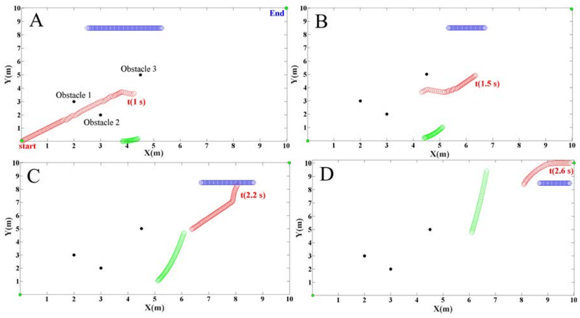
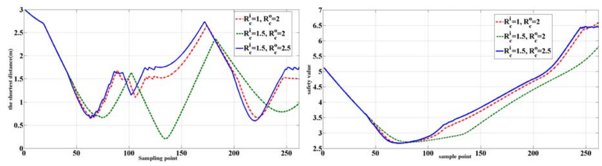


Fig. 5: The trajectory of the UAV in A(0–1 s),B(1–1.5 S),C(1.5-2.2 s) and D(2.2–2.6 s)



(a) The shortest distance of the UAV and obstacles with different parameters

(b) The safety values of the UAV and obstacles with different parameters

Fig. 6: The shortest distance and the safety values of the UAVs

In order to better analyze the performance of the algorithm and the dependence on the parameters, we define **The shortest distance**,d_{tsd}, from the UAV to obstacles.

$$d_{tsd} = \min\{d_{so}, d_{do}\} \tag{32}$$

where, $d_{so} = \min\{d_{so}^1, d_{so}^2, d_{so}^3\}$ and $d_{do} = \min\{d_{do}^1, d_{do}^2\}$. d_{so}^i and d_{do}^j represent the distance from the UAV to the static obstacle i and the obstacle j, respectively.

In addition, we also define **safety value**, η_{sf} to evaluate the performance of the algorithm.

$$\eta_{sf} = \frac{d_{tsd}}{|\vec{v_i} - \vec{v}_{ob}|} \tag{33}$$

where, $\vec{v_i}$ represents the speed vector of the UAV, and $\vec{v}_{ob}$ represents the speed vector of the nearest obstacles. The shortest distance and the safety value of the UAV during the movement are shown in Figures 6(a) and 6(b). Comparing the results in figure 6(a) and 6(b), it can be seen that the algorithm selects parameter $R_c^i = 1.5$, $R_c^o = 2$ to be the best performance.

5.2 Avoidance of multi-UAV

To cope with multi-UAV cooperative collision avoidance problems, simulations with three UAVs are conducted as shown in figure 7. The initial point of the three UAVs are (0,0), (3,0) and (0,2) and the end point of them are (10,10), (8,10) and (10,7). Obviously, the trajectories of the three UAVs intersect in space. The initial conditions and parameters are selected as single UAV. Similarly, we give the shortest distance and safety value for each UAV separately in figures 8(a) and 8(b).

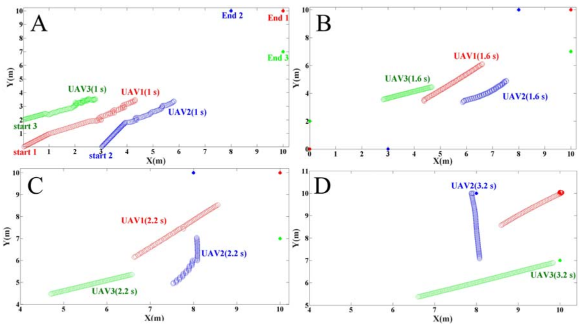
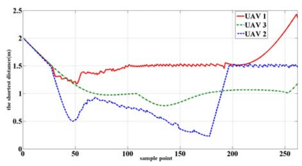
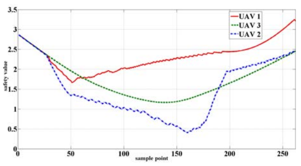


Fig. 7: The trajectory of the three UAVs in A(0–1 s),B(1–1.6 S),C(1.6-2.2 s) and D(2.2–3.2 s)



(a) The shortest distance of the UAV and obstacles with different parameters



(b) The safety values of the UAV and obstacles with different parameters

Fig. 8: The shortest distance and the safety values of the UAVs

Through the adjustment of Algorithm 1, the three UAVs select the appropriate flight trajectory according to the relative position speed.

6 CONCLUSIONS

This study proposed a novel collision avoidance algorithm for fixed-wing UAVs. According to the relative distance and speed between the UAV and the obstacleS, the necessary conditions for avoiding collision are designed. For this idea to be feasible, strict mathematical proof is proposed for illustrating the rationality of the necessary conditions. Based on the necessary conditions, effective obstacle avoidance control can be used to resolve possible future collisions. The simulations manifest the feasibility and performance of the proposed algorithm. Most important future work is to perform a sufficient number of UAVs to analyze the effectiveness of the proposed algorithm.

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