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

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Abstract—In this paper, we study the collision avoidance problem with fixed-wing unmanned aerial vehicles (UAVs). According to the relative spatial position and speed between the drones, the non-conflicting sufficient conditions for conflict detection are proposed. Then an emergency collision avoidance control law is designed based on the proposed conditions to ensure that the UAVs can be driven back to safe state from danger when emergent conflict are detected. Furthermore, a conflict buffer is additionally introduced to prevent frequent switching of control outputs between the "safe mode" and "danger mode". The proposed control strategy cannot only tackle two-UAV conflict scenarios, but has also been extended to multi-UAV conflict scenarios with several additional motion rules. Meanwhile, control input saturation is explicitly considered in the emergency maneuver. Simulation results are presented to illustrate the effectiveness of the proposed methodology.

Index Terms—fixed-wing UAVs, collision avoidance, conflict resolution

I. Introduction

The problem of collision avoidance was first proposed as conflict resolution in route management of civil aviation aircraft, and the collision-free flight path was planned using the collision cone model of the aircraft and the relative speed of the vehicles [1]. With the advent of UAVs these years [2] [3], research on the problem of collision avoidance of drones is developing at an unprecedented rate.

Two kinds of mainstream methods on collision avoidance issues are planning based approaches and optimization based control approaches. Trajectory planning is a typical method for collision avoidance, including planning in advance based on prior environmental information and planning in real time based on online space exploring [4]–[6]. The purpose is to find an optimal and collision-free path for the vehicle. Potential field based trajectory planning has been widely studied. Other methods like sampling based planning have also received much attention. A method based on way-point sampling and pagating a flight path stemming from the start, generates the desired path and checked against the states of the UAV and intrusive obstacle aircraft online [5]. However, planning-based approaches are confronted with a challenge to design a suitable collision avoidance path when the drone has control constraints, as described in [7]. It is also difficult to be generalized to dynamic obstacle scenarios.

For optimization-based control approaches, MPC has been widely studied for collision avoidance of unmanned ground vehicles and UAVs [8]. The problem of collision avoidance is regarded as coupled constraints in the optimization of MPC. Different from path planning approaches, optimization control based methods aim to find an optimal collision avoidance manuver for vehicles. [8] combine the decentralized model predictive control (DMPC) with consensus-based control for multi-vehicle systems like UAV formation for collision avoidance.

Some other research on this issue has also been reviewed. Reachable sets and a real-time path planning algorithm is proposed to tackle the moving collision avoidance problem with motion uncertainties in [4]. A fuzzy steering controller for pedestrian collision avoidance in emergency situations is proposed in [9], which adopts the information from fuzzy training of data in the low-speed stage and generates the collision avoidance control output at high speed. [10] introduced a game theoretic method to tackle priori bounds to generate separations for cooperative vehicles. Control strategies for nonhonlonomic vehicles to safely complete the task while avoiding collisions are proposed in [11].

In spite of so much work on collision avoidance, in the case of fixed-wing UAV, due to the complexity of the aerodynamic model and the coupling characteristics of the control variables, this problem is still a research hotspot [12] [13]. Especially, it is necessary for a UAV to implement an emergency collision avoidance controller which takes the highest control priority when some emergency or very dangerous situation happens, in spite of the flight task or other similar control objectives. To this end, this paper proposes a novel collision avoidance method based on several collision-free sufficient conditions to generate collision-free emergency maneuver. Inspired by the work of [14], an additional conflict buffer is introduced for a smooth transition between the "safe mode" and "danger mode". The proposed collision avoidance method is first designed for two-UAV conflict scenarios, and was then extended and applied to multi-vehicle conflict scenarios with several additional motion rules. The effectiveness of the proposed scheme is evaluated and validated via simulation tests.

II. Problem Overview

A. Model of fixed-wing UAVs

In order to clearly analyze the collision avoidance problem of fixed-wing UAVs when vehicles fly at constant speed and altitude, i.e., performing planar motions. The dynamic model of the UAV is presented as [15]

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

where, (x, y) represents the planar position of the UAV, the variable v indicates the norm of the UAV speed, variables ψ and ω express the heading and the heading rate of the UAV, respectively.

Meanwhile, the turning rate of the UAV is subjected to the constraint:

$$-\omega_{max} \leq \omega \leq \omega_{max} \tag{2}$$

where ω_{max} represents the upper bound of the heading rate.

B. Definitions of regions and concepts

Inspired by the concept of reachable sets in [11], this paper adopts the following definitions of regions (see Fig. 1). From the perspective of UAV i, we employ d_p to represent the distance between the center of UAV i and any other point $\boldsymbol{P}$ within the near airspace.

- Safe region Ω_s: A safe area around UAV i. The radius of this region is usually selected as $R_s > 3l_{ws}$, where l_{ws} represents the wingspan of the UAV.

$$\Omega_s = \{\boldsymbol{P}|0 \leq d_p \leq R_s\} \tag{3}$$

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

- Detection region Ω_d: The perceptible region of UAV i. The distance threshold R_d represents the effective sensing (communication) distance of the UAV.

$$\Omega_d = \{\boldsymbol{P}|0 \leq d_p \leq R_d\} \tag{4}$$

When another vehicle j is outside the detection region of vehicle i, we assume there is no possibility of collision

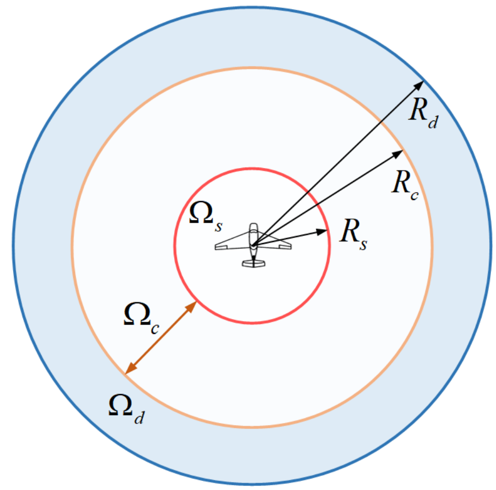


Figure 1. The definitions of regions

conflicts between the two UAVs, since R_d is generally large enough. However, as for other UAVs in the detection region and outside the safe region of UAV i, it would be necessary for UAV i to detect the potential collision conflict and take actions to solve the detected conflict in advance. Thus, the conflict region Ω_c is introduced.

- Conflict region Ω_c: An airspace area outside the safe region for conflict detection and resolution. The distance at which to start the conflict detection is denoted as R_c.

$$\Omega_c = \{\boldsymbol{P}|R_s < d_p \leq R_c\} \tag{5}$$

The distance threshold R_c is designed to be constant for a UAV fly at constant speed, and should be selected in advance. And the principle of the value selection of R_c is presented with the control law in section IV.

Based on the region definitions, two main concepts for further discussion are defined as follows.

Definition 1 (Collision). Given the positions of UAV i and UAV j at time t ($\boldsymbol{P}_i(t)$ and $\boldsymbol{P}_j(t)$), if and only if the distance between the two UAVs is less than twice the safe distance, i.e.,

$$d_{ij}(t) = |\boldsymbol{P}_i(t) - \boldsymbol{P}_j(t)| < 2R_s$$

we say that a collision happens between these two UAVs at this moment.

Definition 2 (Conflict). At time t, a conflict is defined as the case when a collision is going to happen between any two UAVs i and j after some time period Δt, if the two UAVs do not change the heading, i.e.,

$$d_{ij}(t + \Delta t|t) < 2R_s$$

To better analyze the transformation between normal and collision avoidance flight periods, the concepts of "safe mode" and "danger mode" are introduced inspired by the work in [14]. When there is no conflict detected, the UAV is in "safe mode" and control commands are generated with respect to original reference path. However, when there are conflicts detected, the UAV switches into the "danger mode". During this period, the vehicle employs emergency collision avoidance control operations and shields all original mission operations since it has the highest control priority after being activated.

III. Non-conflicting Conditions

Before further discussion, several assumptions should be elaborated:

1) The position and velocity information of all other UAVs within the detection range of UAV i can be transmitted to UAV i without delay.
2) There is no collision between any two UAV i and UAV j at the initial moment in every new control period, e.g., $d_{ij}(t_k) > 2R_s$ for every $k \in \mathbb{N}^+$.
3) The collision avoidance maneuver is finished in a very short time, such that the position change of the UAVs during this period can be neglected.

Then, in each new control period, given the initial state of UAV i and UAV j at time t_k, including the positions $\boldsymbol{P}_i(t_k)$ and $\boldsymbol{P}_j(t_k)$, as well as the speeds $\boldsymbol{v}_i(t_k)$ and $\boldsymbol{v}_j(t_k)$, the initial relative position and speed can be obtained:

$$\begin{aligned}\boldsymbol{P}_{ij}(t_k) &= \boldsymbol{P}_i(t_k) - \boldsymbol{P}_j(t_k)\\ \boldsymbol{v}_{ij}(t_k) &= \boldsymbol{v}_i(t_k) - \boldsymbol{v}_j(t_k)\end{aligned} \tag{6}$$

Without any heading control adjustment, the positions of the two vehicles after a time period Δt are

$$\begin{aligned}\boldsymbol{P}_i(t_k + \Delta t|t_k) &= \boldsymbol{P}_i(t_k) + \boldsymbol{v}_i(t_k)\Delta t\\ \boldsymbol{P}_j(t_k + \Delta t|t_k) &= \boldsymbol{P}_j(t_k) + \boldsymbol{v}_j(t_k)\Delta t\end{aligned} \tag{7}$$

At this point, the relative distance between the two vehicles can be obtained by

$$\begin{aligned}d_{ij}(t_k + \Delta t|t_k) &= |\boldsymbol{P}_{ij}(t_k + \Delta t|t_k)|\\ &= |\boldsymbol{P}_{ij}(t_k) + \boldsymbol{v}_{ij}(t_k)\Delta t|\end{aligned} \tag{8}$$

Denote the angle between vectors $\boldsymbol{P}_{ij}$ and $\boldsymbol{v}_{ij}$ as γ, e.g., $\gamma = arccos\frac{\boldsymbol{v}_{ij}\cdot\boldsymbol{P}_{ij}}{|\boldsymbol{v}_{ij}||\boldsymbol{P}_{ij}|}$, and $\gamma \in [0, \pi]$. Then it is easy to gain that, when $\gamma \in [0, \frac{\pi}{2})$, there is

$$\boldsymbol{P}_{ij} \cdot \boldsymbol{v}_{ij} > 0 \tag{9}$$

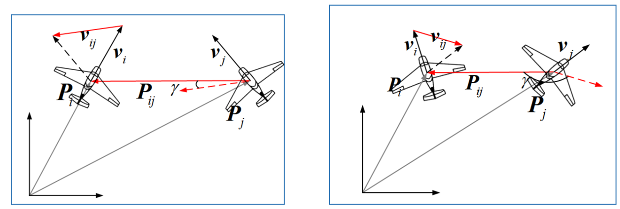
The two UAVs are flying away from each other (as shown in Fig. 2(a)). And when $\gamma \in [\frac{\pi}{2}, \pi]$,

$$\boldsymbol{P}_{ij} \cdot \boldsymbol{v}_{ij} \le 0 \tag{10}$$

the two UAVs will be approaching each other, as shown in Fig. 2(b).

Only in the latter – approaching situations, it is possible that the two UAVs might be conflicting. Assuming that during the approaching process of the two vehicles, $d_{ij}(t) = |\boldsymbol{P}_{ij}(t)|$ reaches a minimum after a period of Δt^*, i.e.,

$$\min d_{ij}(t) = |\boldsymbol{P}_{ij}(t_k + \Delta t^*)|$$



(a) $\gamma \in [0, \frac{\pi}{2})$ (b) $\gamma \in [\frac{\pi}{2}, \pi]$

Figure 2. The relative motion of UAV i and UAV j

Introducing a quadratic minimum,

$$\left.\frac{\partial(d_{ij}(t))^2}{\partial t}\right|_{t=t_k+\Delta t^*} = 0 \tag{11}$$

it can be extended that

$$2\boldsymbol{P}_{ij}(t_k + \Delta t^*)\dot{\boldsymbol{P}}_{ij}(t_k + \Delta t^*) = 0 \tag{12}$$

According to formula (8),

$$\dot{\boldsymbol{P}}_{ij}(t_k + \Delta t^*) = \dot{\boldsymbol{P}}_{ij}(t_k) + \dot{\boldsymbol{v}}_{ij}(t_k)\Delta t^* + \boldsymbol{v}_{ij}(t_k) \tag{13}$$

Then it is manifest that

$$\dot{\boldsymbol{P}}_{ij}(t_k + \Delta t^*) = \boldsymbol{v}_{ij}(t_k) \tag{14}$$

Since $\boldsymbol{P}_{ij}(t_k + \Delta t^*) = \boldsymbol{P}_{ij}(t_k) + \boldsymbol{v}_{ij}(t_k)\Delta t^*$, both sides of the equation are simultaneously multiplied by $\boldsymbol{v}_{ij}^T(t_k)$ to get

$$\boldsymbol{P}_{ij}(t_k + \Delta t^*)\boldsymbol{v}_{ij}^T(t_k) = \boldsymbol{P}_{ij}(t_k)\boldsymbol{v}_{ij}(t_k)^T + \boldsymbol{v}_{ij}(t_k)\boldsymbol{v}_{ij}^T(t_k)\Delta t^* \tag{15}$$

Combining (12) with (14), it can be obtained that

$$\Delta t^* = -\frac{\boldsymbol{P}_{ij}(t_k)\boldsymbol{v}_{ij}^T(t_k)}{|\boldsymbol{v}_{ij}(t_k)|^2} \tag{16}$$

To ensure that there is no collision between the vehicles, the minimum distance between the two vehicles should keeps greater than twice the safety radius, e.g.,

$$\min|\boldsymbol{P}_{ij}(t)| = |\boldsymbol{P}_{ij}(t_k + \Delta t^*)| \ge 2R_s \tag{17}$$

Calculating $d_{ij}^{t_k+\Delta t^*} = |\boldsymbol{P}_{ij}(t_k + \Delta t^*)|$ directly we have

$$\begin{aligned}d_{ij}^{t_k+\Delta t^*} &= \sqrt{\boldsymbol{P}_{ij}(t_k + \Delta t^*)\boldsymbol{P}_{ij}^T(t_k + \Delta t^*)}\\ &= \sqrt{\boldsymbol{P}_{ij}(t_k + \Delta t^*)(\boldsymbol{P}_{ij}(t_k) + \boldsymbol{v}_{ij}(t_k)\Delta t^*)^T}\\ &= \sqrt{(\boldsymbol{P}_{ij}(t_k) + \boldsymbol{v}_{ij}(t_k)\Delta t^*)\boldsymbol{P}_{ij}^T(t_k)}\\ &= \sqrt{|\boldsymbol{P}_{ij}(t_k)|^2 - \frac{|\boldsymbol{v}_{ij}(t_k)\boldsymbol{P}_{ij}^T(t_k)|^2}{|\boldsymbol{v}_{ij}(t_k)|^2}}\\ &= |\boldsymbol{P}_{ij}(t_k)||\sin\gamma(t_k)|\end{aligned} \tag{18}$$

Then an equivalent result of (17) is obtained as

$$\sin\gamma \ge \frac{2R_s}{|\boldsymbol{P}_{ij}(t_k)|} \tag{19}$$

And since $\gamma \in [\frac{\pi}{2}, \pi]$ during the approaching process, the upper formula can be further simplified into

$$\gamma \leq \pi - \arcsin \frac{2R_s}{|\boldsymbol{P}_{ij}(t_k)|}$$

Thus, the sufficient conditions for collision-free flights for any two UAVs i and j are concluded as follows.

Theorem 1. In a new control period k, any two UAVs i and j are non-conflicting if the initial states of the two UAVs satisfy

1) $|\boldsymbol{P}_{ij}(t_k)| > 2R_s$
2) $\gamma(t_k) \leq \pi - \arcsin \frac{2R_s}{|\boldsymbol{P}_{ij}(t_k)|}$

IV. Control Scheme

When any conflicts are detected, the control objective is to drive the UAVs to meet the conditions in Theorem 1 before any collision happens, e.g., when the conflicting neighbor UAV is still in the conflict region.

A. De-confliction Maneuver

In a new control period k, given the initial states of UAV i and UAV j, from the perspective of UAV i, it would be true that $\gamma(t_k) > \pi - \arcsin \frac{2R_s}{|\boldsymbol{P}_{ij}(t_k)|} > \frac{\pi}{2}$. A simple idea is to drive angle γ into set $[0, \pi/2]$, so that the conditions in Theorem 1 can be definitely satisfied. Then the total angle change needed for the two conflicting UAVs is obtained as

$$\Delta\psi_{total} = \gamma(t_k) - \pi/2 = arccos \frac{\boldsymbol{v}_{ij} \cdot \boldsymbol{P}_{ij}}{|\boldsymbol{v}_{ij}||\boldsymbol{P}_{ij}|} - \pi/2$$

It is assumed that the UAVs implement the same collision avoidance control systems. So the conflicting UAVs share the equal collision avoidance responsibilities. Then the desired heading angle change of one UAV is

$$\Delta\psi_d = \frac{1}{2}\Delta\psi_{total} = \frac{1}{2} \arccos \frac{\boldsymbol{v}_{ij} \cdot \boldsymbol{P}_{ij}}{|\boldsymbol{v}_{ij}||\boldsymbol{P}_{ij}|} - \pi/4$$

Thus, the collision avoidance control law is generated:

$$\begin{aligned} u_i &= \rho k_\psi \Delta\psi_d \\ &= \rho k_\psi \left(\frac{1}{2} \arccos \frac{\boldsymbol{v}_{ij} \cdot \boldsymbol{P}_{ij}}{|\boldsymbol{v}_{ij}||\boldsymbol{P}_{ij}|} - \pi/4 \right) \end{aligned} \tag{20}$$

where, parameter ρ is the sign of turning direction, parameter k_ψ in (1/s) is a constant coefficient, which transforms the desired heading change into the desired heading rate. Since the heading change needed for one UAV in this process has an upper bound, e.g.,

$$\Delta\psi_d \leq \pi/4$$

Therefore, we let the minimum heading change sufficient for collision avoidance satisfy:

$$\Delta\psi_{min} = \frac{R_c - R_s}{|\boldsymbol{v}_i|}\omega_{max} \geq \pi/4$$

Then the conflict threshold R_c should satisfy

$$R_c \geq \frac{\pi/4}{\omega_{max}}|\boldsymbol{v}_i| + 2R_s \tag{21}$$

Considering the heading rate constraint of UAVs. Let

$$k_\psi \frac{\pi}{4} \leq \omega_{max}$$

It would be true that $|u_i| = k_\psi \Delta\psi_d < \omega_{max}$.

Denoting the angle difference $\angle{-\boldsymbol{P}_{ij}} - \psi_i$ as ψ_ρ, the direction of heading change can be obtained by:

$$\rho = \begin{cases} -1, & \psi_\rho \in [-\pi, 0) \cup [\pi, 2\pi) \\ 1, & \psi_\rho \in [-2\pi, -\pi) \cup [0, \pi) \end{cases} \tag{22}$$

Let $k_\psi = \frac{\omega_{max}}{\pi/4}$, $R_c = \frac{\pi/4}{\omega_{max}}|\boldsymbol{v}_i| + 2R_s$. Considering the non-conflicting conditions in Theorem 1, the proposed collision avoidance strategy can be refined into the following Theorem.

Theorem 2. For each UAV i in a new control peiod k, facing with an approaching conflicting UAV j at t_k, the following control law:

$$\begin{aligned} & u_i = \rho \frac{\omega_{max}}{\pi/4} \left(\frac{1}{2} \arccos \frac{\boldsymbol{v}_{ij}(t_k) \cdot \boldsymbol{P}_{ij}(t_k)}{|\boldsymbol{v}_{ij}(t_k)||\boldsymbol{P}_{ij}(t_k)|} - \pi/4 \right) \\ & \rho = \begin{cases} -1, & \psi_\rho \in [-\pi, 0) \cup [\pi, 2\pi) \\ 1, & \psi_\rho \in [-2\pi, -\pi) \cup [0, \pi) \end{cases} \\ & \psi_\rho = \angle{-\boldsymbol{P}_{ij}(t_k)} - \psi_i \end{aligned} \tag{23}$$

can successfully resolve the conflict.

Proof. For a n-UAV system with constant speed at v, we take two of them – UAV i and UAV j as examples to verify the effectiveness of the proposed collision avoidance control strategy (23). Angle $\psi_i(t_k)$ and $\psi_j(t_k)$ 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.

It is assumed that there is no collision between the two vehicles at the initial moment, i.e., $|\boldsymbol{P}_{ij}(t_k)| \geq 2R_s$. It is manifest that

$$\arcsin \frac{2R_s}{|\boldsymbol{P}_{ij}(t_k)|} \leq \pi/2 \tag{24}$$

The time of heading adjustment of UAV i for γ_i to satisfy the collision-free conditions is

$$\tau_{ca}^i = \frac{\Delta\psi_d}{|u_i|} = \frac{\pi/4}{\omega_{max}}$$

Then the relative distance change of UAV i during this period is

$$d_\tau^i = |\boldsymbol{v}_i|\tau_{ca} \leq v = \pi/4\omega_{max}$$

Since UAV j takes exact the same collision avoidance scheme, it will has the same contribution to the distance change, e.g,

$$d_\tau^j = |\boldsymbol{v}_j|\tau_{ca} = v\frac{\pi/4}{\omega_{max}}$$

Assuming that the collision avoidance maneuver is implemented at once as long as the conflict is detected, the relative distance at the time when the desired heading change is finished is obtained:

$$\begin{aligned} d_{ij}^{t_k+\tau} &= d_{ij}^{t_k} - \Delta d_{\tau}^{total} \\ &= R_c - (d_{\tau}^{i} + d_{\tau}^{j}) \end{aligned} \tag{25}$$

According to (21), it is obvious that

$$d_{ij}^{t_k+\tau} \geq 2R_s$$

Also, at this moment, the two UAVs both finish the heading change of $\Delta\psi_d$. Thus,

$$\gamma_i^{t_k+\tau} = \gamma_j^{t_k+\tau} = \pi/2 \leq \pi - \arcsin\frac{2R_s}{|\boldsymbol{P}_{ij}(t_k+\tau)|}$$

Both the two sufficient conditions in Theorem 1 are met at $t_k+\tau$, so the conflict is effectively avoided. □

B. Smooth Transition

Due to the dynamic property of the flight, the relative distance between two UAVs may mutate back and forth and thus oscillate near R_c, causing the mode to switch back and forth.This will further result in dithering of the control output.

Therefore, the concept of conflict buffer is introduced to effectively avoid unnecessary mode switching and realize smooth transition of the control outputs (see Fig. 3). The conflict buffer means that the distance threshold R_c^i at which the UAV switches from safe mode into the dangerous mode is smaller than the distance threshold R_c^o at which the UAV switches back to the safe mode from dangerous mode, e.g., $R_c^i < R_c^o$. The ring region between distance of R_c^i and R_c^o from the UAV is called the conflict buffer.

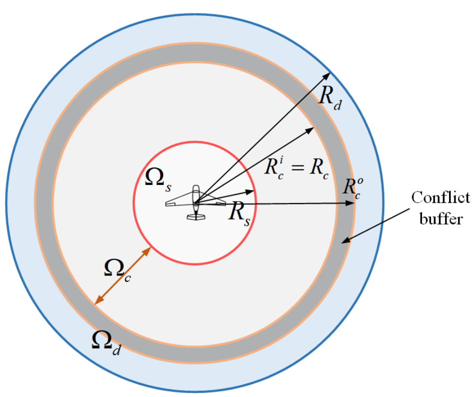


Figure 3. The conflict buffer

C. Case of Multiple Vehicles

Theorem 2 provides scheme to resolve the conflict between any two UAVs. Referring to the law of pedestrian walking, several rules are further introduced to generalize the proposed scheme to the multi-UAV conflict scenarios.

Assuming that UAV i has conflicts with other m vehicles. Then for each conflicting UAV in these m UAVs, a director factor $\rho(\rho \in \{1, -1\})$ and a turning angle u can be generated according to (23). Define the number of $\rho = 1$ as ρ_+ and that of $\rho = -1$ as ρ_-. Then when conflicts are detected for UAV i, calculate the value of ρ_+ and ρ_-, as well as the minimum turning angle u_{min}^+ and u_{min}^-. Then we can obtain the final heading change direction:

$$\rho_i = -\rho_- + \rho_+$$

And the final control output is

$$u_i = \begin{cases} u_{min}^+, & \rho_i > 0 \\ -u_{min}^-, & \rho_i < 0 \\ 0, & \rho_i = 0 \end{cases} \tag{26}$$

Then the complete collision avoidance scheme is summarized in Algorithm 1.

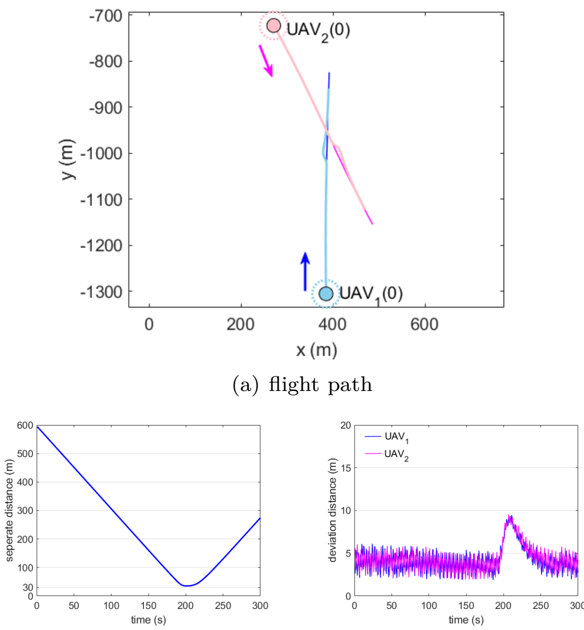
Algorithm 1 Emergency collision avoidance control scheme

```
Initialize parameters: R_d, R_c^i, R_c^o, R_s;
Obtain the state of UAV i: (x_i, y_i) and v_i;
Obtain the information of UAVs in Ω_d of UAV i: (x_j, y_j)
and v_j;
Calculate distance d_ij;
Determine the number of conflicting UAVs: m;
if  m=0 then
    Return;
else if m=1 then
    Calculate the control output by (23);
else
    Calculate the control output by (26);
end if
```

V. Simulations

To test the effectiveness of the proposed method, several simulations are carried out at Matlab 2018. Both two-UAV and three-UAV conflict scenarios are simulated. In the simulation tests, each UAV is functioned as a separate running Matlab thread. They communicate with each other through UDP. The UAVs in the simulation are all equipped with a distributed model predictive controller for path following. The control period is $T = 0.1s$. The cruising speed of the UAV is $19m/s$. The angular velocity limit over the prediction horizon is $0.6rad/s$. The communication distance is $200m$, i.e. $R_d = 200m$. And other parameters are set to be: $R_c^i = 55m$, $R_c^o = 60m$, $R_s = 15m$ (which is much larger than the wingspan of the UAV). Some typical simulation results are presented as follow.

Fig. 4 and Fig. 5 present the simulation results of the proposed collision avoidance control scheme in two-UAV and three-UAV conflict scenarios, respectively. It is showed that in the two-UAV conflict scenario, the UAVs can maintain the separate distance strictly larger than the safety distance $2R_s = 30m$. And in the three-UAV conflict scenario, the minimum separate distance was $24.7m$, which is a little shorter than $2R_s$. Considering the safety distance

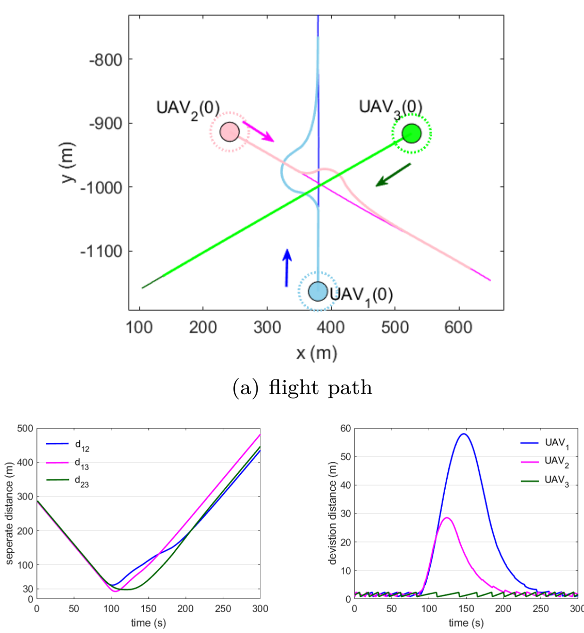


(a) flight path

(b) seperate distance

(c) deviation distance

Figure 4. Simulation of the two-UAV conflict scenario. (a) The start positions of UAVs are signed by shadow circles. (b) The seperate distance between the two UAVs during the simulation. (c) The deviation distance of the two UAVs from the reference paths.



(a) flight path

(b) seperate distance

(c) deviation distance

Figure 5. Simulation of the three-UAV conflict scenario. (a) The start positions of UAVs are signed by shadow circles. (b) The separate distance between the two UAVs during the simulation. (c) The deviation distance of the two UAVs from the reference paths.

which is set to be much larger than the wingspan of the UAVs, and the three-UAV conflict scenarios set in the simulation can hardly happen, the avoidance control scheme can still be regarded as effective.

VI. Conclusions

This papers proposed an emergency collision avoidance scheme for fixed-wing UAVs, which is validated in simulations to be effective in multi-UAV conflict scenarios. Future work will focus on the parameter optimization and field experiments.

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