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Distributed Unmanned Aircraft Collision Avoidance Using Limit Cycle

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Abstract: This paper presents a guidance algorithm for the distributed collision avoidance of multiple unmanned aircraft based on a limit cycle generated around the collision threat. Distributed collision avoidance, on which individual aircraft detects a collision threat and solves it without any explicit communication with the other aircrafts, among multiple unmanned aircraft is performed using the geometric and kinematic information of the existing aircrafts in a discoverable range. The algorithm analyzes the given information by deriving properties such as line-of-sight(LOS) vector, the closest point of approach(CPA), then figures out a collision threat if exists. A limit cycle, which plays a role of a guidance vector field and actually guides the aircraft to maintain predescribed safety radius between the threat and the aircraft, is applied to a stationary and moving obstacles to provide consecutive flight path angles. By doing this, the algorithm eventually guides the aircraft to a collision-free route to accomplish the goal of the given missions. All of these procedures should be processed independently in real-time. Several scenarios are considered for numerical simulations, and the simulaton results demonstrate the effectiveness of the collision avoidance performance and behavioral characteristics of the guidance algorithm. Finally, issues including effectiveness and feasibility of the proposed algorithm are addressed.

Keywords: Collision Avoidance, Limit Cycle, Unmanned Aircraft

1. INTRODUCTION

Unmanned Aircraft(UA) is used for varius missions such as surveillance, target tracking, and partol. A team of UAs can perform more complicated type of mission. That is, cooperative mission can be performed effectively and economically since the team is able to increase the operation range as well as flight duration, and is also appropriate to get multi-channel informations from different locations simultaneously. Each UA should be controlled by itself or remote pilot on the ground control center. The latter is not applicable for the missions that are executed in the area where communication link is unstable, consumes long time duration, or large number of UAs involved in a mission. Thus, the UA must have higher level of autonomy that enables themselves to properly cope with the complicated missions, or unexpected situations such as disconnection with the ground control, malfunction, and pre-uploaded information mismatch. These events might decrease the physical distatnce between UAs since they cannot follow the prescheduled normal flight trajectory. In this case, UAs should have ability to avoid collision between not only an obstacle but also the other aircrafts, even UAs on a same cooperative mission. Since the velocity of the UA is relatively fast compared to other kind of vehicles such as ground vehicle, ships, and mobile robots, every process for collision avoidance should be made in real-time. For this reason, fast and promising collision avoidance strategy is strongly required.

A reactive collision avoidance presented in [1] continuously determines whether or not a collision threat exists. This method uses geometrical and kinematic information of the other vehicles and the UA itself when a collision threat due to the unpredicted events, such as malfunction of the other UAs and lack of geometrical information, occur. If there is a collision threat, attempt to solve it by rectifying the scheduled flight trajectory is made. After a complete resolution of the threat, the UA should be able to resume the original mission. For the fast and promising strategy that guarantees the collision avoidance, reactive method has been developed as one possible solution. In this study, a collision avoidance method is proposed, which predicts a collision threat every step and resolves it by using limit cycle to guide the UA flight away from the collision obstacle. This method has several merits such as small calculation load, easy reflection of dynamic charateristics such as yaw-rate, pitch-rate, velocity, and conciseness based on the intuitive procedures that resemble human's way of dealing with collision threat.

The rest of this paper is devided into four sections. Section II introduces the kinematic model considered in this study, limit cycle derivations, and its global convergence. Section III describes the distributed collision avoidance. Section IV shows the numerical simulation results. Finally, Section V is devoted to summary and concluding remarks.

2. BACKGROUND

2.1 System models

In this study, a fixed-wing UA is considered. It is assumed that a low-level control hierarchy is properly constructed so that given guidance command for the lateral and longitudinal motion of the UA can be fully achieved. Therefore, the following point-mass model is considered as a system model.

$$\dot{x} = u_1 \cos\psi \tag{1}$$

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$$\dot{y} = u_2 \sin \psi \quad (2)$$
$$\dot{\psi} = u_2 \quad (3)$$
$$\dot{z} = \dot{h} = u_3 \quad (4)$$

where (x, y, z) denote the components of three dimensional state vector, ψ and h are flight path angle and altitude, respectively. Control variables u_1, u_2, u_3 represent velocity, turn-rate, and climbing-rate, respectively. These varibles are constrained in order to consider dynamic characteristic as follows:

$$\begin{aligned} V_{min} &\leq u_1 \leq & V_{max}, \\ \psi_{min} &\leq u_2 \leq & \psi_{max}, \\ \theta_{min} &\leq u_3 \leq & \theta_{max} \end{aligned} \quad (5)$$

2.2 Limit cycle

A two dimensional circular limit cycle, which is one of the vector field, generates vectors to circle around a point with radius r or varius shape. A simple limit cycle loitering around a point can be generated (x_1, x_2) with respect to the following differential relations [2].

$$\begin{aligned} \dot{x} &= \frac{u_4}{|u_4|} x_1 + \mu x_2 (r^2 - x_1^2 - x_2^2), \\ \dot{y} &= -\frac{u_4}{|u_4|} x_2 + \mu x_1 (r^2 - x_1^2 - x_2^2) \end{aligned} \quad (6)$$

$$\psi_d = \tan^{-1}(\frac{\dot{y}}{\dot{x}}) \quad (7)$$

where u_4 represents the direction of a limit cycle, therefore, it is a variable that determines the loiter maneuver of a clockwise(CW) or a counter-clockwise(CCW). And, ψ_d is a desired flight path angle at the point (x_1, x_2) to converge into a given limit cycle.

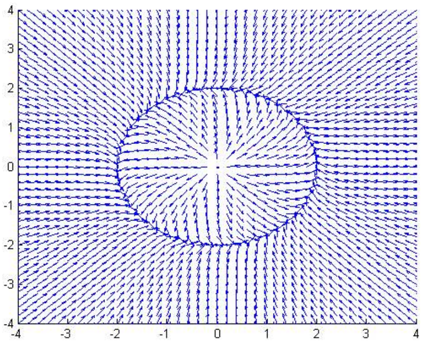

Fig. 1 Phase Portrait of a limit cycle (CCW) .

The UA following the desired flight path angle command ψ_d evnetually converges into the limit cycle and loiters around it. This property enables stationary target tracking for instance. For collision avoidance, limit cycle is generated around a collision threat and is used to fly away from the threat. Factor μ determines how fast the limit cycle converges. Note that the convegence speed become relatively slow as μ becomes relatively small. Convergence of the limit cycle can be proved by Lyapunov stability theory. This method can be used for the standoff target tracking of moving targets. [3-4].

3. DISTRIBUTED COLLISION AVOIDANCE

For the collision avoidance, several steps such as collision detection, collision avoidance, returning to the original mission are necessary to successfully resolve it. Those procedures can be done in a centrallized way or a distributed way. The centrallized collision avoidance could be done by the control of the ground station, and the information including new collision-free trajectory could be transported to the UA. However, this method fails when communication system is unavailable or unstable. On the other hand, in the distributed collision avoidance, every UA independently copes with a collision threat. Therefore, this scheme is more robust since communication with external environment is not required when reliable sensors are eqquipped so that all possible substances are can be sensed.

In this paper, a distributed collision avoidance method using limit cycle is proposed. Collision threat should be detected to avoid it. Sensor systems like radar and camera can be used for the detection of the threat. In this study, it is assumed that existing candidate collision threats are completely detected by the equipped sensor systems. A single as well as multiple collision threat may exist. When multiple collision threats are found, the most threatening one should be distinguished, and the UA should avoid the threat one by one. On the other perspective, multiple threat could be considered as a merged threat and dealt as a single threat, however this approach is not appropriate for threats containing different or time-varying speed. After deciding the threat or obstacle, collision-free flight path should be planned. This can be done by setting imaginary waypoints or generating a trajectory which has distance fair enough from the obstacle in order not to collide with it. Another appoach proposed in this paper provides flight path angle at each position for two dimensional collision avoidance by using limit cycle. For three dimensional collision avoidance, additional pitch angle command also can be used. The subsequent sections explain the procedures for collision avoidance.

3.1 Collision threat detection

Varius types of potential collision threat might exist on route to the target. For example, an aircraft which is on a straight line flight or a constant turn-rate maneuver could be detected. A candidate collision threat should be analyzed to make sure whether or not it is going to collide with the UA when no action was taken. Or, the closest distance between the UA and the threat should be large enough if any action is not taken. The former is considered as a collision threat, and the latter is considered as a candidate collision threat for the time when the analyze is completed. However, this could be continuously modfied since the decisions are made repeatedly every time step as new information is periodcally updated from the sensor systems. The following procedure explains how a candidate collision threat is analyzed with the geographical and kinematic information.

• Step 1. Consider a straght line P connecting U and T, which represents the current position of the UA and the target(goal).
• Step 2. From the position of the n-th candidate collision threat O_n, calculate the distance D_{PO_n} between the line P and O_n

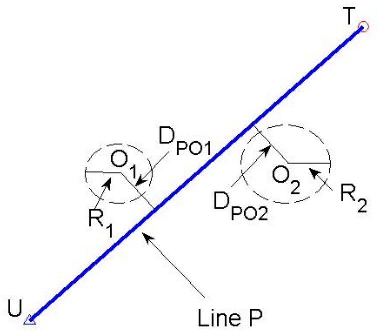

Fig. 2 Non-conflicting geometry.

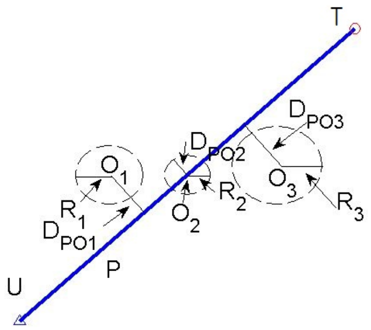

Fig. 3 Conflicting geometry.

• Step 3. Using the velocities of U and O_n, V_u and V_{o_n}, find the closest-point of approach(CPA) and the time of CPA, $t_{n_{cpa}}$, by using the following equations.

$$U(t) = U_0 + V_u t \quad (8)$$

$$O_n(t) = O_{n_0} + V_{o_n} t \quad (9)$$

where subscript 0 represents the time t equals zero. Assuming constant velocity, t_{cpa_n} can be obtained as follows:

$$t_{n_{cpa}} = \frac{(U(t) - O_n(t))(V_u - V_{o_n})}{||V_u - V_{o_n}||} \quad (10)$$

Two objects will be on the CPA after $t_{n_{cpa}}$ seconds. Positive $t_{n_{cpa}}$ means that CPA will appear, on the other hand, negative $t_{n_{cpa}}$ indicates that the two objects were on the CPA. Using $t_{n_{cpa}}$, CPA_{UO_n}, the distance between $U(t)$ and $O_n(t)$, can be calculated as

$$C_{UO_n} = ||U(t_{n_{cpa}}) - O_n(t_{n_{cpa}})|| \quad (11)$$

Candidate collision threat is treated as a collision threat if the following conditions are satisfied.

$$t_{n_{cpa}} > 0 \quad (12)$$

$$C_{UO_n} < R_1 \quad (13)$$

$$D_{PO_n} < R_2 \quad (14)$$

There might be multiple collision threats. In this case, the priority should be determined by comparing $t_{n_{cpa}}$ and C_{UO_n} with proper weightings among the variables, and the most threatening one can be selected for the time.

3.2 Collision avoidance

Limit cycle generated around the collision threat guides the UA to fly by the obstacle while maintaining minimum safety radius, which is the radius of circular limit cycle. For this, the position of the threat O_n is required. By using Egs. (6) and (7), the flight path angle to avoid a collision can be obtained. At this moment, the direction of the limit cycle u_4 should be determined. Manned aircraft usually avoids collision heading right side when a collision threat is found, which is said to be 'Right-of-way rule'. In this study, the rule is adapted so that counter-clockwise is a default direction, and a clockwise maneuver is only allowed for exceptional situations. This situations usually occurs when obstacle's velocity and UA's velocity for avoidance maneuver has same sign with that of obstacle.

3.3 Returning the original mission

After avoiding the obstacle, the UA should return to the original mission. This procedure can be performed by immediately guiding the UA to the target after the collision avoidance maneuver. Heading toward the target, the UA may find a collision threat repeatedly. Iterating aformentioned procedures will eventually guide the UA to the destination safely.

4. SIMULATUON RESULTS

UA should avoid both obstacles with or without CA logic. In this paper, 5 scenarios for numerical simulations are considered to evaluate the performance of the proposed collision avoidance method. UAs are moving toward the target with a constant velocity 30/s, and their maximum turn rate is 0.5deg/s.

4.1 Obstacle without a CA logic

The UA was able to resolve the conflicts as shown in Figs. 4-5. Obstacles with a CA logic do not generate any effort to avoid the collision, but the UA does. Safety radius was set as 300, and the minimum distance between the UA and obstacles were 300.3 as shown in Fig. 4. Figure. 5 considers the obstacles with different safety radius, 300 and 500. The minimum distances were 359.3 and 525.6, respectively.

4.2 Obstacles with CA logic

When all the objects related to the conflict have same CA logic, their strategies are identical. For this reaseon, the trajectory of each object is similar as shown in Figs. 6-8. Slight different trend comes for that the CA action taken was different for each object since simultaneous conflict detection was not made, which depends on the simulation condition.

All the collision conflicts were resolved successfully in spite of that every scenario was written such that ob-

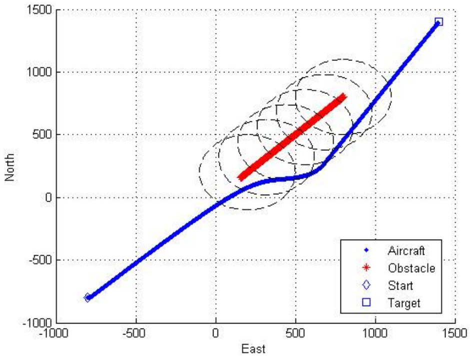

Fig. 4 Head-on conflict resolution.

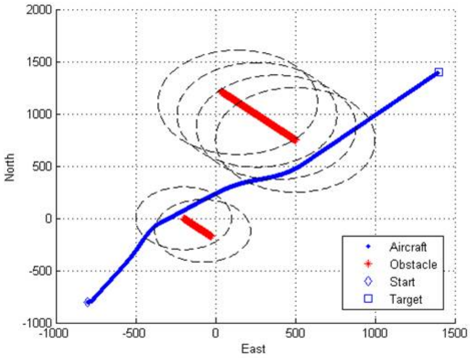

Fig. 5 Multiple conflict resolution.

jects were collide at $(0, 0)$ if there were no CA logic. Safety radius was 300 for all of the scenarios, and no object violated the safety radius.

These results confirm that the CA performance of the proposed method is fair enough to avoid various conflicts . Additional research on the relations between velocities of the UA and the obstacels is required. Of course, the UA should not be slower than a collision threat in order to avoid it.

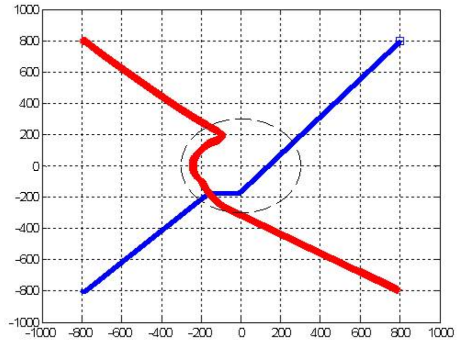

Fig. 6 90degrees Conflict resolution.

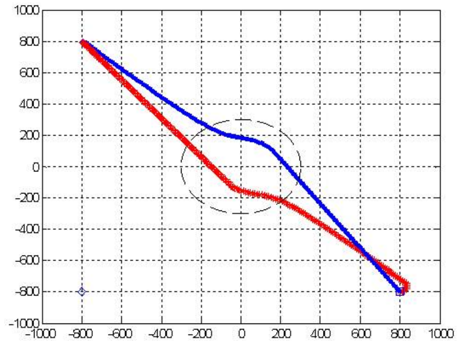

Fig. 7 Head-on conflict resolution.

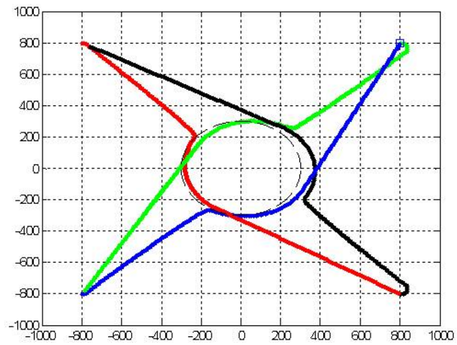

Fig. 8 Multiple conflict resolution.

5. CONCLUSION

5.1 Summary

A distributed collision avoidance method using the limit cycle is proposed, and the performance of the proposed method is evaluated through numerical simulations. Simulation results show that various conflict resolutions were made so that the UA can accomplish the given mission. The efficiency of the algorithm is good enough for real time application, from the fact that average time taken for the simulation for 110 seconds were 2.45 seconds and standard deviations were less than 0.3 seconds.

5.2 Concluding Remarks

Using the concept of the geometrical collision detection and CPA, future conflict was detected and CA maneuver was made. This type of collision detection is useful since not only a present geometry but also a future geometry is considered at the same time. This enables more detail analysis and conservative CA maneuver. Additional research on a velocity guidance and communication strategy between UAs are required for a CA method which consumes less control effort.

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