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Aircraft conflict resolution method based on hybrid ant colony optimization and artificial potential field

Huaxian LIU[1,2], Feng LIU[1,2], Xuejun ZHANG[1,2*], Xiangmin GUAN[3], Jun CHEN[4] & Pascal SAVINAUD[5]

[1]*School of Electronic and Information Engineering, Beihang University, Beijing* 100191*, China;*
[2]*National Key laboratory of Communication, Navigation, Surveillance and Air Traffic Management* (*CNS/ATM*)*, Beihang University, Beijing* 100191*, China;*
[3]*Department of General Aviation, Civil Aviation Management Institute of China, Beijing* 100102*, China;*
[4]*School of Engineering and Materials Science, Queen Mary University of London, London* E1 4NS*, UK;*
[5]*Direction des Services de la Navigation Aérienne* (*DSNA*)*, Reims* 51100*, France*

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Dear editor,
With the significant growth of the civil aviation industry and especially its rapid development in booming economies such as that of China, air traffic flow is drastically increasing, leading to greater congestion around airport terminal areas and in busy airspace [1]. The substantial increase in air traffic flow has intensified the risk of violating safe separation regulations, endangering the airspace operational safety. Furthermore, as the result of this significant growth has resulted in problems such as longer delays, which increase fuel consumption and cost the airline industry billions of dollars every year [2, 3].

Conflict resolution (CR) employs resolution maneuvers to ensure safe separation throughout the entire flight. Resolution maneuvers include changes in velocity, heading angle, or both. It is a critical technique to reduce the risk of collision and improve the airspace efficiency.

Over the past decade, CR has received increasing attention, and many solution approaches have been proposed.

The potential field method, which was originally applied to robot navigation and real-time obstacle avoidance problems, has been extensively investigated in recent years. Tomlin [3] employed the potential and vortex field methods to generate a resolution maneuver strategy for motion planning. In contrast to robots, aircraft operate at high speeds, making the solutions obtained using the potential field methods extremely unrealistic, e.g., generating impractical heading changes, especially when the number of aircraft in conflict increases.

Evolutionary algorithms (EAs) can provide near-optimal solutions, which are widely employed for the CR problem.

The ant colony optimization (ACO) algorithm, which was inspired by the foraging behavior of ants, was proposed as a probabilistic optimization algorithm in 1992 [4]. The core element of this algorithm is based on pheromones. Ants that find food will secrete pheromones on their path, and the following ants will choose this path based on the pheromones left by the first ant. A greater quantity of pheromones on a path will cause a larger number of ants to choose that path. Therefore, a positive feedback phenomenon is estab-

* Corresponding author (email: zhxj@buaa.edu.cn)

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lished between the pheromones and the foraging behavior of the ants, i.e., ants can quickly find the shortest path based on this positive feedback phenomenon. The ACO method makes it possible to obtain a nearly optimal conflict resolution trajectory. However, it suffers from a high computational complexity due to the well-known problem of the curse of dimensionality.

In order to design an effective CR algorithm that considers both efficiency and time for an air traffic controller, his paper proposes a hybrid algorithm as pre-tactical method to maintain safe separation distances between aircraft within a time window of at least 15 min. Experimental studies using illustrative scenarios developed in the previous research showed that our approach outperforms the existing potential field method and EA.

Problem description. The aircraft conflict resolution problem is defined as follows. Aircraft are assumed to fly at the same flight level and in the same horizontal plane. The state X of the i-th aircraft at time t can be expressed as follows:

$$X_i(t) = [v_i(t), r_i(t), x_i(t), y_i(t)], \tag{1}$$

where $(x_i(t), y_i(t))$ is the position, $v_i(t)$ is the speed and $r_i(t)$ is the speed, and $r_i(t)$ is the heading of the i-th aircraft at time t. Because all the aircraft are in the cruise phase and at the same height, their speed is a constant value. Aircraft conflict refers to the risk of collision with other aircraft. Collision and conflict are different concepts in that aircraft collision refers to physical contact between two aircraft, whereas aircraft conflict implies that the distance between two aircraft is less than the safe separation distance. The conflict detection method is shown in Appendix A.

Improved hybrid algorithm. In order to harness the benefits of both methods, this paper proposes an improved algorithm that includes two key steps.

First, the artificial potential field is used to obtain the initial conflict resolution paths. Although these initial paths may not satisfy the physics constraint of the aircraft, they have higher quality than a randomly generated solution.

Second, the results of the artificial potential field are employed to initialize the pheromone matrix of the ant colony optimization algorithm. This step is the core method used to improve the performance and efficiency. The "authority" ants are introduced, and their foraging paths are the adjusted paths generated by the artificial potential field. Algorithm 1 shows the flowchart of this initialization procedure.

Algorithm 1 Procedure of improved hybrid algorithm

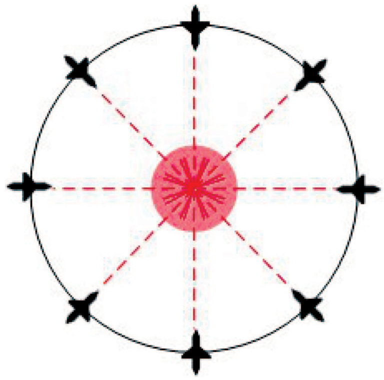
Input:
The starting points and destinations of the aircraft.
Output: (refer to Appendix D)
(1) CL: computational load;
(2) F: feasibility;
(3) SE: system efficiency;
(4) CP: conflict probability.
Step 1. Initialize the ant colony (refer to Appendix C).
Step 2. Get authority ant using artificial potential field.
(1) Set aircraft number;
(2) Calculate the flight path of an aircraft by function B(6) in Appendix B;
(3) Adjust the path and encode it as the authority ant's path.
Step 3. Generate the authority ant colony.
Copy authority ant's path Ps times.
Step 4. Whether satisfy the conditions?
(1) Satisfy: Output optimization results: CL, F, SE and CP;
(2) Not satisfy: go to step 5.
Step 5. Whether satisfy the conditions?
The ants choose the path by C(1) in Appendix C.
Step 6. Whether satisfy the conditions?
(1) Update the pheromone using C(2) in Appendix C;
(2) Return to step 4.

Experimental studies. A typical scenario [5–9] was used to test the proposed method, as shown in Figure 1(a). In the classical scenario, all aircraft are uniformly distributed in a circle with a radius of 100 n mile, and each aircraft flies along a straight path.

The cruising speed (V) of the aircraft is set to 1000 km/h and the safe separation distance is 5 n mile.

This part of the experiments aimed to evaluate the efficiency of the improved algorithm by comparing it with the artificial potential field method and the ant colony optimization method using the classical scenario.

The results calculated based on 10 independent runs of the four algorithms were statistically analyzed in terms of their conflict probability, average computational load, feasibility, and system efficiency; these results are listed in Figure 1(b). It can be seen that as the number of aircraft increases, the improved algorithm achieves a more significant improvement. Although not all the values for the improved algorithm are the best ones, they show its overall superiority in terms of safety and efficiency. For example, when the number of aircraft is 28, the computational loads of the four algorithms are 6.1, 260.4, 210.5, and 23.2. The value of the improved algorithm is much smaller than the results for the ACO and GA, and only a slightly greater than the value of the artificial potential field. Moreover, the improved algorithm has the best system efficiency and conflict proba-



(a)

Number	Artificial potential field				Genetic algorithm				Ant colony optimization				Improved algorithm			
	CL (s)	F	SE	CP	CL (s)	F	SE	CP	CL (s)	F	SE	CP	CL (s)	F	SE	CP
2	3.2	2	0.96	0	5.7	0	0.90	0	6.2	0	0.91	0	6.1	0	0.93	0
4	3.4	4	0.94	0	13.6	0	0.87	0	15.9	0	0.88	0.0013	10.0	0	0.92	0
6	3.6	6	0.93	0	25.7	0	0.85	0	24.3	0	0.87	0	11.1	0	0.90	0
8	3.9	8	0.92	0	41.2	0	0.78	0.003	36.1	0	0.80	0.0025	14.9	0	0.90	0
12	4.3	12	0.91	0	84.6	0	0.72	0.0045	63.4	0	0.73	0.0038	16.0	0	0.88	0
16	4.6	16	0.90	0	123.5	0	0.60	0.007	98.4	0	0.63	0.0038	17.2	0	0.87	0.00021
20	5.0	20	0.89	0	170.9	0	0.45	0.01	131.3	0	0.56	0.0025	19.6	0	0.86	0.00036
24	5.5	24	0.88	0	221.7	0	0.35	0.12	169.2	0	0.49	0.0050	21.9	0	0.85	0.00042
28	6.1	28	0.86	0	268.3	0	0.30	0.23	210.5	0	0.46	0.0053	23.2	0	0.84	0.00060

(b)

Figure 1 (Color online) (a) Classical scenario; (b) comparisons of artificial potential field, genetic algorithm, ant colony optimization, and improved algorithm used for classical scenario (CL, F, SE, and CP stand for computational load, feasibility, system efficiency, and conflict probability, respectively).

bility. We can see that the hybrid algorithm has the advantages of both the ACO algorithm and the artificial potential field. In addition, in the real scenario, the solutions obtained by the improved algorithm are in compliance with the requirements of actual engineering applications. More details of the experimental study can be found in Appendices E–G.

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Supporting information Appendices A–G. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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