Cooperative search-attack mission planning for multi-UAV based on intelligent self-organized algorithm

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A B S T R A C T

This paper proposes an intelligent self-organized algorithm (ISOA) to solve a cooperative search-attack mission planning problem for multiple unmanned aerial vehicles (multi-UAV). This algorithm adopts the distributed control architecture which divides the global optimization problem into several local optimization problems. Each UAV is able to solve its own local optimization problem, and then make the optimal decision for the multi-UAV system through the information exchange among UAVs. The search-attack mission planning process is divided into two phases, the one is waypoints generation under constraints of UAV's maneuverability, collision avoidance and maximum range, the other is path generation which takes account of the threat avoidance. In the first phase, an improved distributed ant colony optimization (ACO) algorithm is presented to carry out the mission planning and generate waypoints. Considering the range constraint of UAV, a new state transition rule is designed to guide UAV back to its initial point within the maximum flight range. In the second phase, Dubins curve is employed to smoothly connect the waypoints generated by the ACO. As for the unexpected threats during the flight, an online threat avoidance method is proposed to replan the paths. Finally, simulations are carried out to analyze the convergence performance, external responsiveness and internal scalability of the proposed ISOA for the multi-UAV search-attack mission planning problem.

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1. Introduction

Unmanned aerial vehicle (UAV) swarm is a typical multi-agent system which can be controlled autonomously or remotely and execute missions without pilots. Compared with the manned vehicles, UAV has the prominent advantages on executing the dull, dirty and dangerous tasks. Due to the limitations when a single UAV is on a mission, it is of great importance to take advantage of the cooperation of multiple UVAs (multi-UAV), to obtain higher operation efficiency [1]. U.S. Department of Defense released the document "Unmanned Aircraft System Roadmap" which proposed the division method of UAV's autonomy capability level, and pointed out that the multi-platform cooperation is an important development trend of UAV techniques [2,3].

The architectures of multi-UAV autonomous cooperative control are usually divided into two types: the centralized control architecture and distributed control architecture [4]. The centralized control method is the dominant strategy in the early researches with the advantage of getting global optimal solution, but a fatal

disadvantage is that the multi-UAV system will be out of control once the decision-making layer fails. Along with the improvement of UAV's performance and autonomous capability, the distributed control method with superiorities of higher reliability, less computation and communication becomes a research focus [5,6].

The multi-UAV cooperative control strategies are usually divided into two types: top-down and bottom-up [7]. The top-down approach is mainly based on the idea of hierarchical solution by decomposing the original problem into several subproblems, and solving the subproblems through negotiation and cooperation between platforms. The optimization algorithms to solve the problems include exact optimization algorithms and heuristic algorithms. Exact optimization algorithms such as Branch and Bound (BAB), Branch and Cut (BAC), Dynamic Programming (DP) are able to obtain the optimal results [5]. However, these algorithms have large computation when the problem has hard side constraints. For this problem, some heuristic algorithms such as Particle Swarm Optimization (PSO) [8], Ant Colony Optimization (ACO) [9] and Genetic Algorithm (GA) [10] have been proposed recently. Furthermore, some improved heuristic algorithms were proposed, such as Bello-Orgaz designed a multi-objective GA (MOGA) for solving a complex mission planning problem [11,12]. Although these

algorithms reduce the computation, they are still computationally intractable for online planning in dynamic environments with complex constraints.

On the contrary, the bottom-up approach which originates from insect community focuses on the optimization and coordination strategy on the basis of individual's response to outside environment [13,14]. The swarm would act with self-organized behavior through individual's local perception and interaction. Yang proposed a decentralized self-organized control algorithm of swarm robot for target search and trapping inspired by bacteria chemotaxis [15]. This algorithm performs less vulnerability to local optimum, and high computational efficiency. Di designed a distributed receding horizon optimization to obtain the optimal motion of UAVs without violating the collision avoidance and network connectivity constraints [16]. Evers considered the appearance of the new targets during the flight, so-called time-sensitive targets, and then presented an online stochastic UAV mission planning algorithm, which aims at generating a path with maximum expected profit of targets and replanning path to deal with the time-sensitive targets [17]. Recently, a distributed search-attack mission self-organization algorithm (SAMSOA) was presented for a search-attack mission planning problem, which improved the efficiency of task execution significantly [18].

Due to the large computation and poor response time of the top-down methods, the bottom-up approach is adopted in this paper. In addition, the existing bottom-up algorithms usually ignore the following factors: i) the constraint of UAV's maximum range; ii) collision avoidance among UAVs or between UAVs and the obstacles; iii) lack of scalability for a UAV's join or exit. Therefore, we aim to solve the search-attack mission planning problem of multi-UAV system with considering above factors in this paper. Different from the results in the literature, the main contributions of this paper are as follows.

(1) For the cooperative search-attack mission planning problem of multi-UAV, an intelligent self-organized algorithm (ISOA) is proposed, which is composed of waypoints generation module and path generation module. The former module is designed by an improved distributed ACO algorithm, while the latter module is designed by Dubins curve.
(2) For this multi-UAV cooperative search-attack mission planning problem, not only the maneuverability constraints, collision avoidance constraints and threat avoidance constraints are considered, but also the range constraints are considered, which has not been addressed in the literature. The range constraints are added into the state transition rules of ACO algorithm. At each decision step, the ISOA would evaluate the rest range for each UAV, to ensure that they can be back to initial point or a specific destination within maximum range.
(3) When a threat is detected, the path generation module of ISOA would select a safe middle waypoint, and then replan a flyable path to avoid the threat. The threat avoidance path is designed based on the Dubins curve, to online avoid the unexpected threats.
(4) The ISOA is designed based on the bottom-up strategy. Each UAV has the ability to online sense the battlefield environment and make decision by itself. Therefore, when a UAV joins or exits, the existing UAVs can adjust their motions to realize the multi-UAV cooperation. The ISOA is characterized by the highly real-time, reliability and flexibility because of the bottom-up strategy.

The rest of this paper is organized as follows. In section 2, the multi-UAV cooperative search-attack mission planning problem is described. In section 3, the online ISOA is proposed which can be divided into waypoints generation and path generation. In sec-
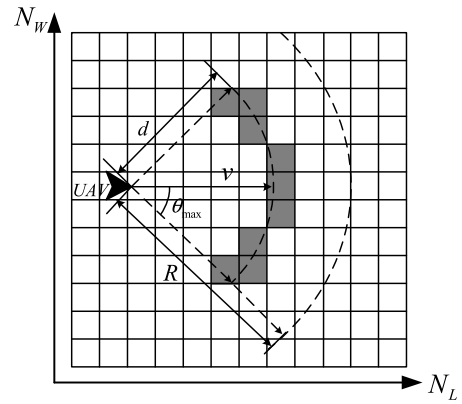
tion 4, simulations are conducted to verify the effectiveness of the ISOA. Finally, a conclusion is given in section 5.

2. Description of multi-UAV cooperative search-attack mission planning problem

2.1. Battlefield environment model

Battlefield environment is complex and changeable. To solve the cooperative search-attack mission planning problem of multi-UAV, some assumptions need to be given first.

Assumption 1. The UAVs are isomorphic and each UAV can execute both search and attack mission.

Assumption 2. All UAVs fly in a same constant velocity and have a same maximum range.

Mission area. The real UAV is in the three-dimensional space which makes the planning problem of the multi-UAV complex. According to [19], the UAV's motion can be decoupled into two motions in two-dimensional plane and vertical direction, respectively. Therefore, the mission area here is two-dimensional.

Mission planning scenario. The relevant elements of mission planning scenario can be represented by a 4-tuple $\{E, V, T, C\}$. E is the battle field environment including the threats and no-fly zones. $V = \{V_1, V_2, \cdots, V_{N_v}\}$ represents the multi-UAV system with size of N_v. $T = \{Target_1, Target_2, \ldots, Target_{N_t}\}$ is the set of N_t targets distributed in the mission area whose information is unknown. The two main tasks of UAVs are the search and attack. C represents the constraints of UAV.

Discrete mission area. Mission area of the UAVs is modeled as a $N_L * N_W$ grid map as shown in Fig. 1. Then the motion of the UAV is embodied as the motion in the discrete grid point. Suppose that the detection radius of UAV is R and then the targets appeared within detection circle can be discovered by the UAV. Maneuverability constraints limit the possible positions at the next time instant. Considering the maximum turning angle θ_{max} and displacement d in unit time, the gray grids in Fig. 1 represent the possible positions of UAV at the next time instant.

2.2. Cooperative search-attack mission optimization model

The multi-UAV cooperative search-attack mission is an online planning problem which aims at finding and destroying the targets as many as possible in a dynamic and complex environment. Thus

Fig. 1. Discrete mission area.