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A self-organized search and attack algorithm for multiple unmanned aerial vehicles

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A R T I C L E I N F O

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A B S T R A C T

This article presents a novel distributed algorithm for multiple unmanned aerial vehicles (UAVs) to solve the online search–attack mission self-organization problem under adversarial environment. The distributed search–attack mission self-organization algorithm (SAMSOA) divides the global optimization problem into some local optimization problems. Each UAV is considered as a subsystem and is assigned a separate processor to solve its local optimization problem. Meanwhile, the information exchange between UAVs can help each subsystem make the optimal decision for the multiple UAVs system. The SAMSOA algorithm consists of a normal flight mode and a threat avoidance mode. In the normal flight mode, the search–attack mission is modeled to maximize the surveillance coverage rate and minimize the targets' existence time. Then, the improved distributed ACO algorithm is designed to generate path points. Finally, a Dubins curve is used to connect the path points smoothly. In the threat avoidance mode, the path of avoiding a threat is generated based on Dubins curve. A series of simulations are carried out to verify the online application of the proposed SAMSOA algorithm.

1. Introduction

UNMANNED aerial vehicles (UAVs) have been widely used because of their zero casualties, low cost and the advantages of size, speed and maneuverability. UAVs are expected to gradually become the main battle weapon in the Air Force around 2020 and will partly replace manned fighters and bombers to account for most of the air defense and strike missions [1]. According to Observe-Orient-Decide-Act (OODA) model and the U.S. Department of Defense's UAV autonomy roadmap, UAVs' autonomy capability can be divided into 10 levels: remotely guided, real time health/diagnosis, adapt to failures & flight conditions, onboard route replan, group coordination, group tactical replan, group tactical goals, distributed control, group strategic goals and fully autonomous swarms [2–4]. Multi-UAV cooperative combat is an important development trend.

The structure of a multi-UAV autonomous cooperative control system is usually divided into three types: the centralized architecture, distributed architecture with central node and distributed architecture without central node. Then, the specific strategies in solving multi-UAV cooperative mission planning problem are mainly divided into two types: top–down and down–top. The top–down structure is the dominant strategy with the better performance in decomposing problems. The mission planning problem can be decomposed into mission allocation and path planning. Schumacher proposed a method based on the mixed integer linear program (MILP) to solve optimal timing of air-to-ground tasks. Specifically, a scenario where multiple air vehicles are required to prosecute geographically dispersed targets is considered [5]. Artificial intelligent algorithm is frequently used in solving the complex optimal problems because of its quick convergence. Wang Zhenhua presented an application of the multi-objective ant colony system (MACS) algorithm to the UAVs route planning problem based on Voronoi diagram. The MACS algorithm concept was introduced and modified to accommodate the route planning situation [6].

Meanwhile, the down–top structure emphasizes each individual's response to outside environment hence has good adaptivity. Recently, the research on multi-UAV cooperative mission self-organization has been developed rapidly. Kim considered simultaneously search and attack task allocation of a team of heterogeneous UAVs that performs a search and destroy mission in an environment where multiple targets are of various types possessing different values. A distributed approach was proposed to address search planning and attack task allocation issues simultaneously in one framework and performs better when comparing with other methods [7]. Kumar investigated algorithmic development for cooperative control of a number of UAVs engaged in fighting a wildland fire. The tasks of cooperative tracking of a

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Nomenclature

v	speed of UAV	m/s
N_v	number of UAVs in multiple swarm system	
R	radius of UAV detection range	m
$\theta_{\max}$	maximal turning angle of UAV	deg
d	displacement of UAV per time step	m
L, W	length and width of the discrete mission area	
J_r	evaluation function in searching mission	
J_a	evaluation function in attacking mission	
D	damage degree of the target caused by each attack	
ω	weighting coefficient in evaluation function of whole system	
μ_i, ω_i	weighting coefficient in evaluation function of subsystem	
$d_{\min}$	safety distance between UAVs	m
R_T	radius of threats	m
d_t	minimum distance between UAV and threats	m
$R_{\min}$	minimum turning radius of UAV	m
V_{gain}	gain obtained from food	
$\Delta\tau_{l_0}$	local pheromone attenuation coefficient	
$\Delta\tau_{g_0}$	global pheromone update coefficient	
F	uncertainty coefficient of environment	
δ	coefficient of effect range caused by discovered food	
η	heuristic function	
α, β	coefficients in heuristic function	
N_t	iteration threshold in state transition rule	
λ, ζ	angles in Dubins curve calculation	deg
ϕ	exit and entry angle in Dubins curve calculation	deg

fire front for accurate situational awareness and cooperative, autonomous fire fighting using fire suppressant fluid are formulated based upon optimization of respective utility functions, and then a decentralized control method for the cooperative UAVs is developed [8]. He considered the formation constraints for multiple UAVs. For example, to avoid collision, they should not come close to each other. Similarly, to avoid broken communication links, they should not wander far away. However, he did not consider the maneuverability constraints of a single UAV, such as the minimum turning radius. Schouwenaars presented a framework for provably safe decentralized trajectory planning of multiple autonomous aircraft [9]. Each aircraft planed its trajectory individually using a receding horizon strategy based on (MILP). Additionally, a priori safe rescue solution was provided in case the problem was too complex to be solved within the time constraints of a real-time system. In this research, the constraint of UAVs' maneuverability had been taken into account. However, in these researches the problem of how to avoid the unexpected threats had not been mentioned.

Summarizing recent researches, there are two key problems which are still needed to be further studied when designing a multi-UAV system mission self-organization algorithm: one is how to ensure the norm operation of the system in case of internal changes, such as, a UAV joins or leaves the task, which is called scalability; the other is how to ensure the norm operation of the system in case of external changes, such as, the appearance of unexpected threats.

To solve these two problems we proposed a novel self-organized algorithm for multi-UAV system with specific mission of search and attack.

(1) The designed algorithm consists of a normal flight mode and a threat avoidance mode. Each UAV in the swarm can operate alone as a subsystem and different UAVS can work cooperatively through the exchange of information.

(2) Under the normal flight mode, an improved distributed ant colony optimization (ACO) algorithm based algorithm is presented to organize the search–attack mission online and a Dubins curve is used to smooth the path.

(3) Under the threat avoidance mode, a threat avoidance algorithm is designed to avoid the threats detected in the normal flight mode, which has great significance in improving the survival rate of UAVs.

Especially, the self-organized algorithm is designed down–top under the structure of distributed architecture without central node which is the inevitable choice to satisfy the current requirements imposed by environment which demand flexibility, adaptivity, reconfigurability and responsiveness [10–12].

2. Search–attack mission self-organization problem description

The multi-UAV mission self-organization problem is how to execute a mission cooperatively through the UAVs sense of battlefield environment and information exchange between UAVs, and how to adjust each UAV behavior spontaneously to ensure stable operation of the multi-UAV system in case of internal and external changes.

To solve the multi-UAV mission self-organization problem, some assumptions are given first.

Assumption 1. The UAVs in the multi-UAV swarm are isomorphic and every UAV can execute both search and attack.

Assumption 2. All UAVs fly in a constant altitude with the same constant velocity. Therefore, the mission space can be simplified to be two-dimensional space.

When conducting the reconnoitering mission, each UAV searches the mission area with the goal of maximizing the surveillance coverage rate in order to find the most targets. When conducting the attacking mission, the UAVs work cooperatively to destroy the target as soon as possible. During the whole search–attack mission period, the UAV swarm alternately conducts the searching and attacking mission.

Given the UAV activity area in two-dimensional space, the mission area is discretized to a grid map with size of $L \times W$. Fig. 1 shows the detection range of a UAV with radius of R in the discrete mission area. The area within the detection circle can be detected. The grey grids are the possible positions at the next time instant.

Definition 1 *(Surveillance coverage rate).* Surveillance coverage rate is the ratio of grids which have been searched to all the grids in mission area. It can be calculated by

$$P = \sum_{x=1}^{L}\sum_{y=1}^{W} node_{x,y}/L \times W, \quad node_{x,y} \in \{0, 1\} \tag{1}$$

where the value of $node_{x,y}$ can be 0 and 1. $node_{x,y} = 0$ means the grid (x, y) has not been searched and $node_{x,y} = 1$ means the grid (x, y) has been searched.

The goal of the searching mission is to maximize the surveillance coverage rate in order to find the most targets. The evaluation function in this mission is

$$J_r = P \tag{2}$$

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