Advances in Cooperative Target Searching by Multi-UAVs

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Abstract. With the development of multi-UAVs technology, detecting and searching unknown areas by using autonomous multi-UAVs have become a frontier research direction with difficult in this field. To illustrate the progress of cooperative target searching by multi-UAVs, firstly, the significance of cooperative searching and its application in military and civil fields are systematically described. Then the current research status of the multi-UAVs cooperative searching is described, and three aspects are analyzed, including environment modeling, cooperation architecture and searching methods. Finally, the conclusions are made in terms of the autonomous and cooperation ability of multi-UAVs. The future research trend of improving the efficiency of multi-UAVs cooperative search is discussed and prospected from the perspectives of UAVs' perception, cognition, autonomy, as well as human-machine cooperative technology.

Keywords: Multi-UAVs · Swarm intelligence · Target searching · Environment modeling · Cooperative architecture · Search method

1 Introduction

Swarm UAVs technology involves the design, construction and deployment of large-scale UAV group to solve problems or perform tasks in a cooperative manner [1]. Due to the limited mission capabilities of a single UAV, the performance of multi-UAVs system is superior to that of an independent individual UAV system through effective cooperation between UAVs [2]. Multi-UAVs system has unique system attributes and functions such as high robustness, scalability and flexibility, which makes the execution of complex tasks more effective and reliable [3]. With the development of multi-UAVs technology, it plays an increasingly important role in military and civil field. In military, with the development of science and technology and the deepening of information warfare, robots have become the best choice to perform dull, hash and dangerous tasks. For example, in recent years, the frequent occurrence of Predator, Global Eagle and other combat UAVs in the Afghan and Syrian wars shows the advantages of UAVs in reconnaissance and search. In civil, the rapid development of multi-UAVs technology has gradually changed people's lifestyle and working style, such as in forest areas where fires occur,

Y. Tan et al. (Eds.): ICSI 2022, LNCS 13345, pp. 25–34, 2022.
https://doi.org/10.1007/978-3-031-09726-3_3

multi-UAVs plays an important role in the troubleshooting of thermal power plant [5]. Therefore, multi-UAVs cooperative search technology is a crucial technology for modern war, civil rescue and other activities.

The autonomous control system of UAV means that the system can automatically generate optimal control strategies, complete various strategic tasks, and have fast and effective task adaptive ability without human intervention through online environment perception and information processing [6]. Challenges faced by UAV systems include complex, unstructured dynamic environments, and various real-time external threats and accidents. The U.S. Department of Defense believes that the first technology for future UAVs is to increase autonomy and collaboration, all tasks of UAV systems depend on autonomous environmental awareness. Therefore, how to achieve high efficiency cooperation of swarm autonomous UAVs in complex environment is the key to the research of multi-UAVs cooperative search. This paper will review the research progress of multi-UAVs cooperative target searching technology around the environment modeling, cooperative architecture and searching method in multi-UAVs cooperative target searching.

2 Advances of Key Technologies for Multi-UAVs Cooperative Target Searching

The US military proposed the concept of swarm UAVs operation in the late 1990s. At present, the requirement for intelligent control of UAV is increasing, as shown in Fig. 1, the U.S. Department of Defense classifies the Autonomous Control Level (ACL) of an UAVs system into 10 levels [7]. With the improvement of the autonomy of the UAVs system, the UAVs system has different requirements from remote control (level 1) to full autonomy (level 10), the corresponding perception, coordination and decision-making of the UAVs system have different requirements. In the area of UAVs system, US Predators (RQ-1/MQ-1) and Global Eagles (RQ-4) can achieve ACL 2 to 3, while Joint UAV(J-UCAS) and X47-B can achieve ACL 5 to 6. Unmanned combat armed rotator (UCAR) achieves ACL 7 to 9. However, most UAVs systems are still at a low level of autonomy, so it is necessary to combine swarm UAVs with specific task requirements to improve the autonomy of the UAV and the efficiency of performing operational tasks.

At present, the multi-UAVs technology has become the frontier hot spot in the research of swarm intelligence [8]. Most of the literatures on the theory of swarm UAVs cooperation focus on the research of the algorithm of swarm UAVs cooperation. For research on algorithm and simulation of swarm UAVs cooperation, the research directions include swarm UAVs autonomous formation [9], swarm UAVs cooperative target searching [10], swarm UAV cooperative area coverage [11], swarm UAVs cooperative target allocation [12]. For the problem of multi-UAVs cooperative search, due to a variety of uncertain factors, the search environment is dynamic. Many fruitful works have been carried out on the research of multi-UAVs cooperative target searching technology in complex environment, most of which are focused on three aspects: environment modeling, cooperation architecture and search method.

For the research of swarm UAVs cooperation technology, we must start from the characteristics and task requirements of UAVs. Firstly, we need to model the environment

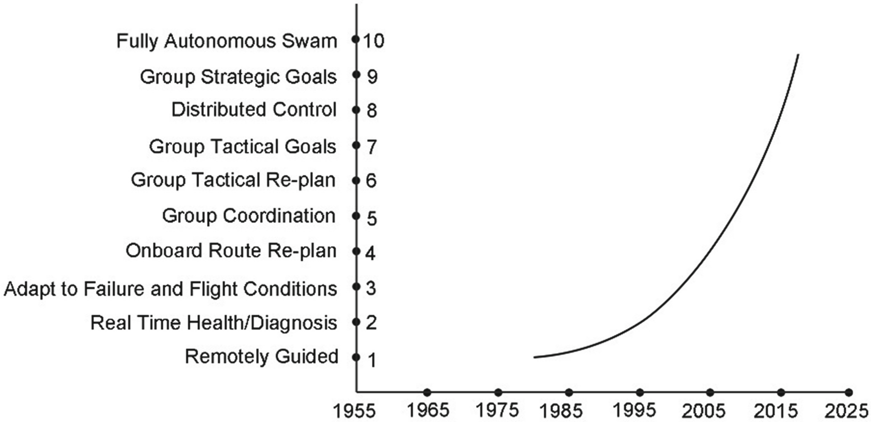

Fig. 1. The autonomous control level of UAV defined by AFRL and the development of UAV autonomy system.

according to the task requirements, and then improve the efficiency of UAVs completing the task through appropriate swarm UAVs cooperation architecture and search method. This paper analyzes and discusses the environment modeling, cooperation architecture and search method in the cooperative search of swarm UAVs.

2.1 Environment Modeling

The main methods of environment modeling of swarm UAVs cooperation include grid method, artificial potential field method and graph theory method. Grid method divides the task environment of UAVs into several grids at fixed interval, as shown in Fig. 2, in the task area of $L_X \times L_y$, the task area is divided into $M \times N$ grids according to the Δd interval distance, the size of a single grid directly affects the memory required by the computer to store environmental information. Environment grid search maps mainly include target probability map, digital pheromone map, return map, and search maps generated by different methods. Artificial potential field is a method to model the task environment based on the attractiveness of the target and the repulsion of the threat, swarm UAVs can achieve obstacle avoidance search of the target under the combined action of target gravity and threat repulsion. Graph theory method divides the area into several sub-areas based on the terrain and environmental characteristics of the area, and combines the task characteristics of each sub-area to assign search tasks and plan flight routes for UAVs. The more common method is based on Voronoi, as shown in Fig. 3.

Song et al., proposed a swarm robots search algorithm based on neural network, corresponding the neural network to the grid environment, and constructed a digital pheromone map [13]. Pehlivanoglu et al., and Zhang et al., constructed multiple robots cooperative area models based on Voronoi to achieve search coverage for unknown environment [14, 15]. Zheng et al., divided the area to be searched into several sub-areas, calculated the probability of the existence of the target in each area, constructed the target probability map, and achieved the multi-UAVs cooperative search dynamic target

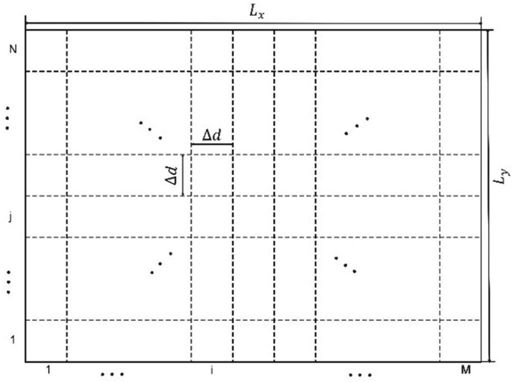

Fig. 2. Area division based on grid method.

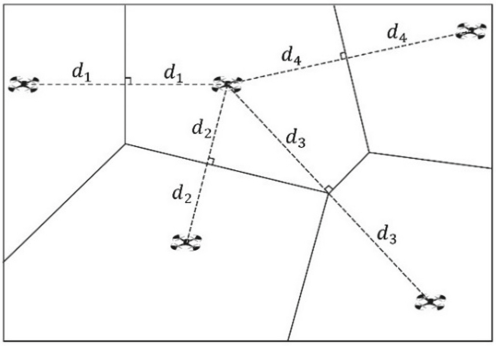

Fig. 3. Area division based on Voronoi.

in unknown environment [16]. Zhen et al., rasterized the UAV task area and represented the threat area in a grid map, built the environmental cognitive model of target attraction field and threat repulsion field, and built the target probability map based on the grid map [17].

2.2 Cooperation Architecture

In order for swarm UAVs to accomplish the complex tasks in a cooperative manner, an architecture for controlling its movements must be established. The main task of the autonomous control system for UAVs is to connect each sub-system into a whole, manage and dispatch each sub-system in a unified way, so that each sub-system can complete the overall task in unison, and an excellent autonomous control system can improve the efficiency of multi-UAVs task completion. Multi-UAVs control systems are generally divided into centralized architecture, distributed architecture and hybrid architecture.

As shown in Fig. 4, it is the centralized architecture, which has a control center, all the information of the UAVs should be sent to the control center centrally, and all the information in the system will be processed centrally. The centralized architecture is relatively simple and the system management is convenient, but when the number of UAVs is large, the computational complexity of the centralized control method increases significantly, resulting in a significant reduction in the work efficiency of UAVs. When the control center fails, the whole system will be paralyzed [18]. Wei et al., adopted an architecture of centralized control of multi-UAVs in the case of a small number of UAVs, and realized the coverage search of the task area by operating the actions of multi-UAVs through the control center [19].

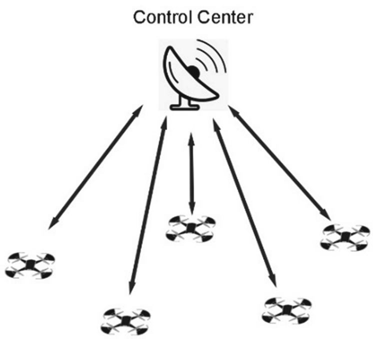

Fig. 4. Centralized architecture.

As shown in Fig. 5, it is a distributed architecture, which adopts the way of autonomy and cooperation, the complex solution problem is divided into sub problems that can be solved by each UAV. There is an equal cooperative relationship between UAVs, and they can communicate directly. Distributed architecture can increase the number of robots and has high flexibility. It is suitable for workspace in dynamic environment. At present, most multi-UAVs cooperation methods use distributed architecture. Li et al., and Bakhshipour et al., used the distributed architecture on the cooperative search of multi-UAVs [20, 21].

Fig. 5. Distributed architecture.

The hybrid architecture is the integration of the first two architectures, with a distributed architecture between the swarm UAVs, and a centralized architecture between the swarm UAVs and the control center, as shown in Fig. 6. The hybrid architecture combines the advantages of the two structures to make the swarm UAVs more intelligent. Hou et al., adopted a hybrid architecture to divide the swarm UAVs into multiple groups, the UAVs in each group can communicate with each other, and the leading UAV in each group can communicate with each other, so as to realize the communication between groups, and each group is centrally controlled by the control center [22].

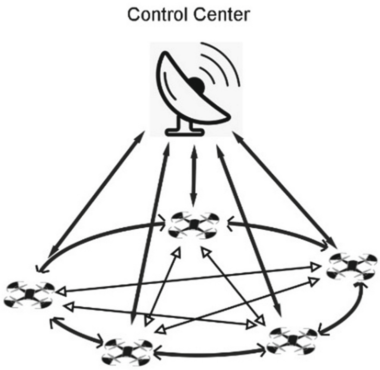

Fig. 6. Hybrid architecture.

2.3 Cooperative Searching Method

For the multi-UAVs cooperative target searching task in unknown environment, from the perspective of scalability and applicability, this paper focuses on the scanning search method, dynamic search method and intelligent optimization method.

Scanning search method mainly searches the task area for the purpose of area coverage. This method can ensure that UAVs can traverse the whole area. Common scanning search methods include parallel search and spiral reconnaissance [23]. As a simple and practical coverage search method, the scanning search method has the advantages in searching for static targets, but it has poor adaptability to dynamic environment. Because it mainly focuses on area coverage, the time efficiency under the target search task is not as efficient as other methods.

Dynamic search methods mainly include discrete Markov decision-making process and distributed Model Predictive Control (DMPC). Dynamic search algorithm is widely used in complex multi-UAVs cooperative target searching task because of its simple calculation and fast response to dynamic events. Elamvazhuthi et al., and Zhou et al., divided and modeled the environment, added information to the environment based on discrete Markov chain, and combined the constructed model with other advanced algorithms to complete the cooperative search task of multi-UAVs [24, 25].

Model Predictive Control (MPC) uses the control system model and optimization technology to design the optimal control input of the system for a predictive cycle. The core idea is to solve the problem by rolling optimization. DMPC uses a distributed structure to improve the decision-making speed of the whole system. Zhao et al., Lun et al., and Yu et al., controlled the motion of UAVs based on DMPC, and solved the problem of cooperative search of multi-UAVs in unknown environment [26–28].

In the multi-UAVs cooperative search problem, the current related research is mostly based on intelligent optimization methods. Traditional optimization methods have less application because of the rapid increase of time and space complexity and poor solution results when solving large-scale problems. The concept of swarm intelligence first appeared in cellular robotic systems proposed by Beni and Wang in 1989 [29]. Intelligent optimization methods derive from intelligent behaviors of cooperation between biological groups, for example, inspired by the behavior of social groups of organisms such as bird flocks, ants, bats, wolves, and plant populations [30]. Numerous studies have shown that intelligent optimization algorithms can be applied cooperative control of multi-UAVs, and can improve the efficiency of UAVs in solving problems in complex environments. Common intelligent optimization algorithms include particle swarm algorithm, ant colony algorithm, bat algorithm, gray wolf optimizer, bean optimization algorithm and bacterial colony algorithm.

MD et al., proposed a new particle swarm algorithm based on motion coding for multi-UAVs searching for dynamic targets [31]. Hta et al., proposed a new adaptive robot grey wolf optimizer algorithm to solve the cooperative search target problem of swarm robots in unknown environment. An adaptive speed adjustment strategy was used to track the dynamic target, and compared with other methods, this method has obvious advantages in the efficiency of target searching [32]. Wang et al., constructed an intrusion model of dynamic targets, and proposed an improved bat algorithm for his model to solve the trajectory optimization problem of UAVs tracking the intrusive targets [33]. Not limited to the research on social animal groups, the adaptive strategy of plant population also provides novel ideas for the research of swarm intelligence and swarm robots, and a swarm UAVs search algorithm based on the evolution of plant population distribution is constructed [34, 35], and effective simulation experiments are carried out for the problem of pollution source search. Kyriakakis et al., used moving peak to simulate the movement of multiple UAVs searching for multiple moving targets [36]. An online multi-population framework was constructed, which is suitable for most intelligent optimization methods and meets the experimental requirements of multi-UAVs searching for multiple targets in unknown environments.

3 Research Summary and Prospect

The main problem of multi-UAVs cooperative target searching technology is how to make full use of the autonomy, cooperation and reduce the time and space complexity of the algorithm. In recent years, swarm intelligence and machine learning technology have been gradually introduced into the multi-UAVs cooperative problem. The application of these technologies makes the UAVs have stronger self-learning and self-organization ability in complex environment. The complexity of the algorithm is lower than other traditional algorithms. The combination of distributed architecture and centralized architecture makes UAVs fleet more cooperative, enabling swarm UAVs to remain cooperative to complete tasks even when a single UAV fails or is threatened by the environment.

With the increasing complexity of task environment, there is no effective means to achieve the autonomous control of UAVs in dynamic unknown complex environment and time-sensitive situation, and to achieve fast and effective acquisition and processing of information and the control ability of the platform. The contents that need further research on the autonomous control technology of swarm UAVs systems include:

(1) The comprehensive environmental awareness and intelligent battlefield situation awareness capabilities of the UAVs. Due to the harshness and complexity of the battlefield environment, the impact of emergencies such as single UAV failures and threat in the environment cannot be ignored when performing target searching tasks. In the future, UAVs need to have a more comprehensive environmental awareness, be able to timely perceive and respond to changes in the battlefield environment, improve the awareness of the battlefield situation, and achieve better search results.
(2) Human-machine intelligence integration and learning adaptability. Operators should give proper guidance to multi-UAVs systems in order to achieve more accurate control, how to use the characteristics of each human-machine effectively to achieve the integration of human-machine intelligence, and how to design a more efficient control structure of human-machine cooperation system to improve the usability and overall operational efficiency of multi-UAVs systems is the further research content to improve the cooperative efficiency of multi-UAVs systems.
(3) The autonomous navigation, planning and control capabilities of the UAVs under complex conditions. In order to realize the in-depth cognition of complex environment of swarm UAVs, future UAVs systems should establish intelligent development mechanism, which can make UAVs systems have similar stable learning and intelligent development mechanisms to human beings, improve the self-learning, self-reasoning and self-organization capabilities of UAVs systems, and give full play to the real-time decision-making advantages of swarm UAVs. Enhance the ability to cope with complex environment, such as combining traditional methods with swarm intelligence and machine learning, to make UAVs more autonomous.

4 Conclusion

This paper systematically combs the problem of multi-UAVs cooperative target searching. The key technologies of target searching, including environment modeling, cooperative architecture and search method, are discussed in depth. The development trend of multi-UAVs cooperative target searching is analyzed. The key to improve the efficiency of multi-UAVs cooperative search is to improve the autonomy and cooperative capability of multi-UAVs system. Multi-UAVs system has made great progress in self-organization and cooperative control of UAVs. The integration of swarm intelligence and other methods enables multi-UAVs to have certain autonomous decision-making ability. In the future, for complex unknown environment, improving environment modeling method, improving UAVs perception and cognitive ability, designing a more reasonable cooperative architecture, realizing more efficient human-machine cooperative control technology, building swarm self-learning and intelligent development mechanism will greatly improve the effectiveness and efficiency of multi-UAVs cooperative target searching.

Acknowledgements. This research was funded by Qinghai Natural Science Foundation project under grant number 2020-zj-913, Anhui Natural Science Foundation project under grant number s202202a04021815, Anhui Graduate Scientific Research project under grant number yjs20210087.

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