Physica A 491 (2018) 127–141

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Modeling and simulation of dynamic ant colony's labor division for task allocation of UAV swarm

Husheng Wu [a], Hao Li [b], Renbin Xiao [c,*], Jie Liu [b]

[a] School of Equipment Management and Support, Armed Police Force Engineering University, Xi'an 710086, China
[b] Air Force Early-Warning Academy, Wuhan 430019, China
[c] School of Automation, Huazhong University of Science and Technology, Wuhan 430074, China

HIGHLIGHTS

- In this paper, we introduce our method for dynamic task allocation problem of unmanned aerial vehicle.
- A new dynamic ant colony's labor division (DACLD) model is proposed, which also has a better practicability in various multi-agent systems.
- DACLD can meanwhile get both UAVs' states and real-time positions, and has high degree of self-organization and flexibility under dynamic environments.

ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form 29 June 2017
Available online 14 September 2017

Keywords:
Ant colony's labor division
Dynamic task allocation
Response threshold model
UAV swarm

ABSTRACT

The problem of unmanned aerial vehicle (UAV) task allocation not only has the intrinsic attribute of complexity, such as highly nonlinear, dynamic, highly adversarial and multi-modal, but also has a better practicability in various multi-agent systems, which makes it more and more attractive recently. In this paper, based on the classic fixed response threshold model (FRTM), under the idea of "problem centered + evolutionary solution" and by a bottom-up way, the new dynamic environmental stimulus, response threshold and transition probability are designed, and a dynamic ant colony's labor division (DACLD) model is proposed. DACLD allows a swarm of agents with a relatively low-level of intelligence to perform complex tasks, and has the characteristic of distributed framework, multi-tasks with execution order, multi-state, adaptive response threshold and multi-individual response. With the proposed model, numerical simulations are performed to illustrate the effectiveness of the distributed task allocation scheme in two situations of UAV swarm combat (dynamic task allocation with a certain number of enemy targets and task re-allocation due to unexpected threats). Results show that our model can get both the heterogeneous UAVs' real-time positions and states at the same time, and has high degree of self-organization, flexibility and real-time response to dynamic environments.

1. Introduction

With the rapid development of technology, unmanned aerial vehicle (UAV) can work in different complicated or uncertain environments, and has been extensively used to perform various military tasks including surveillance, recon-

* Corresponding author.
E-mail address: rbxiao@hust.edu.cn (R. Xiao).

http://dx.doi.org/10.1016/j.physa.2017.08.094
0378-4371/

naissance, attack, and damage assessment, etc. But there are some limits in weapons, ammunition, detection equipment and speed of a single UAV, which makes it difficult to separately complete complex multi-objective reconnaissance and massive attack missions. Naturally, UAV swarm (which consists of many heterogeneous UAVs) combat gradually attract increasing military attention because of its better robustness through redundancy and faster tasks accomplishment, and has being done extensive research as a new style in the future battlefield [1]. As is known to all, the core of UAV swarm combat lies in its complex task allocation problems under dynamic environment. The objective of task allocation is to maximize total reward obtained by destroying various targets which have different attributes, and maximize the overall operational effectiveness of UAV swarm under the premise of meeting various tactical and technical indexes. This problem presents some complex features, such as highly nonlinear, dynamic, highly adversarial, multi-modal, etc. Previous studies mainly focused on static task allocation and gave more attention about two important parts, modeling and solving algorithms.

As for task allocation model, due to the uncertainties and complexities in the dynamic battlefield, some scholars extend and improve several optimization models such as multiple traveling salesman problem (MTSP) [2], job shop scheduling problem (JSSP) [3], mixed-integer linear programming (MILP) [4] and multiple processors resource allocation (MPRA) [5], vehicle routing problem (VRP), etc. In [6], the task assignment of cooperating UAVs is classified as the polygon visiting multiple traveling salesman problem (PVMTSP) which can be solved by two proposed algorithms using genetic fuzzy; In [7], multiple UAVs' mission planning is modeled as a vehicle routing problem with time window and precedence requirements; Moreover, capacitated vehicle routing problem with time windows (CVRPTW) model, which has better ability to describe complicated battlefield scenarios, has been used in modeling for the planning problem of cooperative search mission carried by "Predators" and "Global Hawk" [8]. In [9], a heuristic task allocation method combining VRP and MILP is proposed to carry out various tasks of different time windows at various locations using a fleet of heterogeneous UAVs. For more complex task allocation problems, in [10], a cooperative multi-tasks the allocation problem (CMTAP) model was proposed, which can give a good description of the temporal relationship among different tasks and scheduling constraints.

Algorithms of solving task allocation problem are mainly divided into two categories: the centralized algorithms and the distributed ones. There are many centralized algorithms such as enumeration method, dynamic programming, branch-and-bound procedure, etc. Moreover, increasing researchers give more extensive attention on intelligent optimization algorithms, such as genetic algorithm (GA) [11], particle swarm optimization (PSO) [12], ant colony optimization (ACO) [13], wolf pack algorithm (WPA) [14], and cat swarm optimization (CSO) [15], etc. Although the centralized algorithms are easy to understand and can theoretically obtain the optimal scheme of task allocation, the huge computational complexity is a great challenge for center node. In addition, without fully using self-adaptation and cooperative characteristic of intelligent agents, the performance of the results obtained by centralized methods may be very ordinary, even poor in the dynamic environment [16]. While, the distributed algorithms fully consider the information interaction between heterogeneous UAVs, which is helpful for solving dynamic task allocation problem. Generally speaking, the distributed algorithms can be divided into two types: top-down and bottom-up. The top-down ones are mainly based on the ideas of layered hierarchical and divide-and-conquer, which decomposes the original problem into several sub-problems so as to solve those sub-problems well through consultations and cooperation among each other. There are many top-down methods, such as decentralized Markov decision process (Dec-MDP), distributed model predictive control (DMPC), dynamic distributed constraint optimization (DDCOP), contract net (CN), auction algorithm and other methods based on market auction mechanism [17]; While the bottom-up algorithms mainly focus on the optimization and coordination strategies based on stress response and behaviorism. Moreover, the bottom-up algorithms emphasize individual dynamic response to environment, and can emerge the global self-organization behavior through individual's local awareness and response interaction. Because of its simple calculation and good robustness, many researchers use it to solve complex task allocation problems [18].

These previous studies can be adopted for solving the problem of static task allocation (to UAV) in a straightforward manner. However, for the dynamic task allocation of UAV swarm combat, these approaches are weak in some important considerations: (1) The battlefield is highly uncertain and dynamic, while many current related studies based on static model have very ordinary real-time performance [19]; (2) UAV Swarm is composed of heterogeneous UAVs, while the UAVs' resource consumption and multiple attributes (such as flight speed, fuel consumption, stealth or anti-stealth and attack ability) are often not fully taken into account; (3) It is difficult to deal with task re-allocation due to unexpected enemy targets of which situation often emerges in actual battlefield. Meanwhile, especially for task allocation problem with a large number of UAVs, which is not suitable to apply centralized control or global model, swarm intelligent methods give a good solution to these complex distributed problems [20].

Actually, there are many similarities between biological collective behavior and tactical actions of UAV Swarm, including formation flying, cluster attack, cooperative reconnaissance and defense. Therefore, inspiration by biological systems, we can get better models and solutions for task allocation problem of UAV Swarm under complex battlefield environment. As is known to all, there are various biological collective behaviors, such as wolf pack hunting, ant colony foraging, birds migrating, shoal feeding, cattle resisting attack, etc. [21]. Among them, the labor division is one of the most important characteristics of ant colony, bee colony, wolf pack, fish school and other social creatures [22]. In 1996, Bonabeau [23] et al. proposed fixed response threshold model (FRTM) which is a classical ant colony's labor division model. It has advantages of modeling and implementing easily, and can reflecting the flexibility of complex problems of task allocation. And then, it has been continuously improved and widely applied in task allocation problems [24], management of enterprise production [25],