Hierarchical System Architecture Design of UAV Cluster Based on Mission Requirements

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Abstract. Through the complexity analysis of UAV cluster, based on three modes of task, cluster management and control behavior, and information interaction behavior, the complex system element set, interaction relation set, complex criteria set, and complex feature set are summarized into the backbone architecture level of collaborative task subsystem, cluster management and control subsystem, and networking communication subsystem. And completed a variety of models, multiple levels and multiple types of sub member architecture level, comprehensive build a can not only the overall task oriented, and geared to the neseds of local task, to based on the global situation and based on the local situation, both can rapid response and can avoid conflict collaborative decision-making and execution of complex unmanned aerial vehicle (uav) cluster system architecture.

Keywords: UAV · Cluster of Drones · Layered Network

1 Introduction

Through the complexity analysis of UAV cluster, based on three modes of task, cluster management and control behavior, and information interaction behavior, the complex system element set, interaction relation set, complex criteria set, and complex feature set are summarized into the backbone architecture level of collaborative task subsystem, cluster management and control subsystem, and networking communication subsystem [1]. And completed a variety of models, multiple levels and multiple types of sub member architecture level, comprehensive build a can not only the overall task oriented, and geared to the needs of local task, to based on the global situation and based on the local situation, both can rapid response and can avoid conflict collaborative decision-making and execution of complex unmanned aerial vehicle (UAV) cluster system architecture [2].

Geared to the needs of different tasks, unmanned aerial vehicles (UAVs) based on hierarchical type cluster complex system architecture design, from the collaborative task, cluster control, network communication system analysis and design including three task oriented unmanned aerial vehicle clustering hierarchy type collaborative task architecture and behavior model [3], the hierarchical cluster model and the hierarchical control architecture and behavior type network communication architecture and behavior model [4].

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2 Task-Oriented Hierarchical Collaborative Task Architecture Design of UAV Cluster

According to the characteristics of UAV cluster scale, rapid response to task and grasp situation change, a task-oriented hierarchical cooperative task architecture for UAV cluster is adopted [5].

According to the requirements of broad spectrum mission capability of UAV cluster, the characteristics of task styles are analyzed, which are divided into the distributed cooperative mode of single-task layer cooperative task, the centralized cooperative mode of single-task chain cooperative task, and the multi-level distributed cooperative mode of multi-task hybrid task.

For jamming, identity-strike, search-identity-strike, search-identity-relay and other single-mission chain closed-loop cooperative tasks, UAV cluster adopts centralized cooperative mode [6]. For single task collaborative tasks such as collaborative penetration, collaborative interference, collaborative search and collaborative identification, the UAV cluster adopts the distributed collaborative mode. For multi-missile cooperative jamming - multi-missile cooperative identification - multi-missile cooperative strike, multi-missile cooperative search - multi-missile cooperative identification - multi-missile cooperative strike, multi-missile cooperative search - multi-missile cooperative identification - multi-missile cooperative relay and other mission layer and mission chain hybrid cooperative missions, UAV cluster adopts multi-level distributed cooperative mode.

2.1 Distributed Collaborative Mode

For the single-task cooperative task styles such as collaborative penetration, collaborative interference, collaborative search and collaborative identification, the UAV cluster can be seen to be composed of various weapon units with consistent functions and equal roles, and there is no primary or secondary or functional serial among the clusters. Adopt the distributed collaborative mode, unmanned aerial vehicle within the cluster point-to-point communication, adopt the method of autonomy and cooperation to solve the problem of global control, to be able to see from the complex problems into a child of each node in the system to solve the problem, and then by each node calculation, give full play to the autonomous ability of each node cluster has the scalability, enhance the combat effectiveness.

2.2 Centralized Synergy Model

Aimed at "Jam-identity-strike, search-identity-strike, search-identity-relay" single task chain loop style of collaborative task, such as unmanned aerial vehicles by different functions and roles of each cluster weapons units, according to the function of serial cluster tasks, form the task chain relationship, centralized collaborative model are adopted to decrease the system complexity, reduce the communication cost produced by negotiation between nodes, improving system flexibility and rapidity.

2.3 Hierarchical Distributed Collaboration Model

Disturbance in play the synergy - play the synergy identification - more collaborative blow, play collaborative search - more collaborative recognition - play more cooperative combat, play collaborative search - more collaborative recognition - play play mixed relay tasks such as layer, task chain collaborative task style, unmanned aerial vehicle cluster by more units of different functions and roles of weapons, Same type unmanned aerial vehicle on a single mission collaborative task, and perform the task chain between different types of unmanned aerial vehicle closed loop task, using a multi-level distributed mode, all information through multiple master node for processing, and have more child nodes under each of the master node, the master node and use different frequencies for communication between child nodes, between the master node USES the distributed collaborative architecture, Centralized collaboration mode and distributed collaboration mode can be adopted in child nodes. This mode can realize the perception and decision from local situation to global situation according to the constraint information such as communication capability and node size, and improve the overall task efficiency of nodes. To achieve the large-scale, efficient and conflict-free execution and operation of the cluster, and improve the flexibility of UAV cluster tasks.

3 Task-Oriented Hierarchical Cluster Management and Control Architecture of UAV Cluster

In cluster management and control, the cluster management and control process is generally divided into four processes, namely, autonomous task decision, dynamic task allocation, cluster route planning and cooperative formation control. In order to realize the coordination of autonomous task decision, online dynamic task allocation, cooperative flight path planning, cooperative formation control and other functions of UAV cluster, a dynamic multi-level distributed cluster management and control architecture is designed.

Among them, in autonomous task decision-making, decision nodes are determined or polling decisions are made at the level of UAV cluster, task subgroup and machine cluster subgroup according to the situation, and cluster tasks are decided according to the battlefield situation.

In dynamic task allocation, the execution unit is determined according to the decision task situation, task execution subgroup size and cluster resource status, and the task allocation is completed.

In the cluster flight path planning, the cluster sub-group realizes the real-time flight path planning of each flight platform in the cluster sub-group according to the flight status of individuals in the group, the mission target position information or the patrol flight track point information.

In the formation cooperative control, the flight control quantity of the task execution individual and the formation is calculated, and the flight attitude of the weapon platform is adjusted in real time, so that each UAV platform can fly along the formation track planned by the flight path planning layer, and achieve the desired task of the top-level decision.

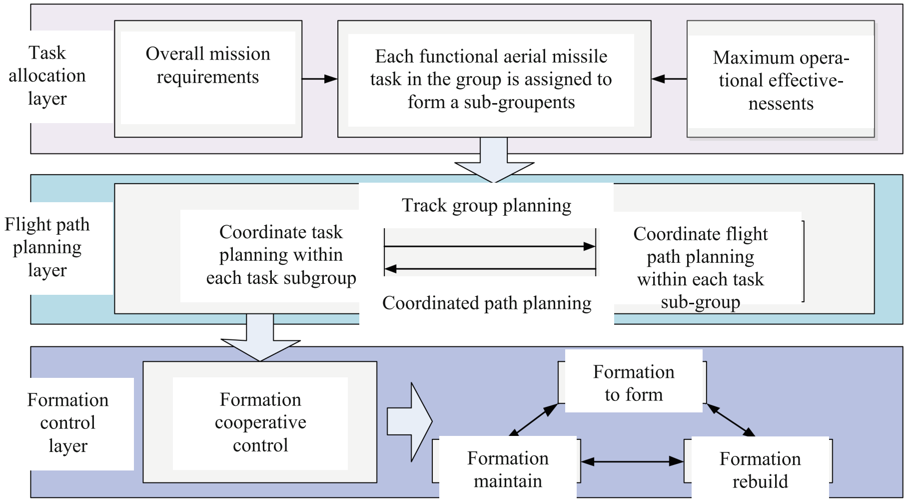

Fig. 1. Three-layer management mode under mission layer cooperation of UAV cluster

For UAV cluster tasks, the task requirements and cluster state information are analyzed, which are divided into task layer collaboration and task chain collaboration, and the corresponding cluster management and control mode is designed.

3.1 Task-Oriented Collaborative Three-Layer Cluster Management and Control Mode

From the analysis of cooperative task style in the task layer, UAV cluster is usually composed of UAVs with the same function and the individuals in the group complete the same task, or composed of UAVs with different functions but the function difference is not obvious or does not affect the task effect. In this regard, UAV clustering only involves allocation, planning and control in the cluster, not decision-making. The UAV cluster management and control architecture under the cooperation of the task layer is designed as a three-layer management mode, namely, the decision allocation layer, the flight path planning layer and the flight control layer. The specific architecture is shown in the Fig. 1.

Among them, the task allocation layer is at the top of the task cluster management architecture, which mainly completes the assignment of UAV cluster task groups, and determines the task subgroup scale, function configuration and execution unit according to the task type. The flight path planning layer is mainly carried out in each task subgroup. Through the calculation of one or several UAVs, the flight path planning of each UAVs in the task subgroup is completed, and the desired flight path of the formation is provided. The formation control layer is mainly carried out between each UAV and the UAV. By calculating the UAV flight control quantity, the cluster formation can be controlled to fly to the target point along the desired flight path obtained by the track planning.

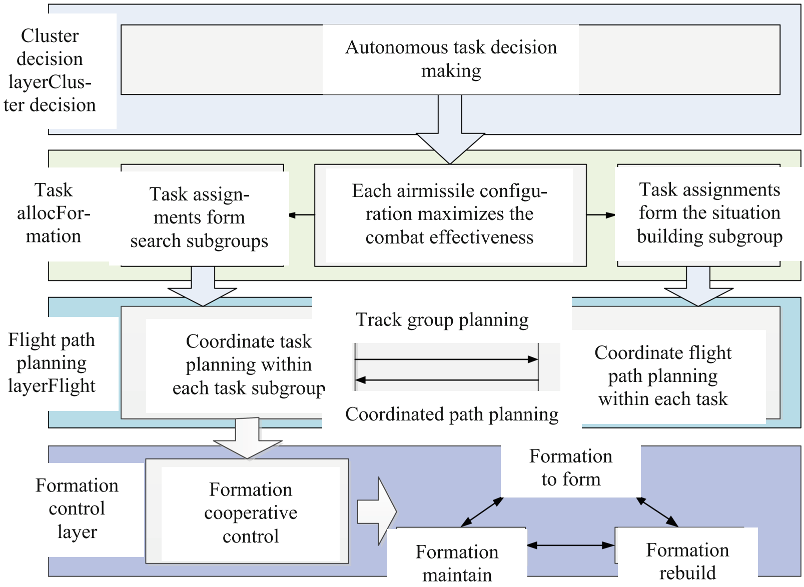

Fig. 2. Four-layer management mode under the cooperation of UAV cluster task chain

3.2 Task Chain-Oriented Cooperative 4-layer Cluster Management and Control Mode

The analysis of the cooperative task style of the task chain shows that the tasks are connected in the way of the task chain, which has a certain spatial and temporal cohesion. In terms of structure, the UAV cluster is composed of multiple functional UAVs in order to perform a variety of different tasks. However, the dynamic battlefield situation makes the UAV cluster can complete the task transformation according to the situation change at any time in the task process, that is, the UAV cluster needs to have the corresponding autonomous decision-making ability. After completing the task decision, it is necessary to have the task allocation and dynamic adjustment of each UAV in the cluster. In this regard, the UAV cluster under the cooperation of task chain involves the whole process of decision-making, allocation, planning and control in cluster management. Then, the UAV cluster management and control architecture under the cooperation of the task layer is designed as a four-layer management mode, namely, the cluster decision layer, the task allocation layer, the flight path planning layer and the formation control layer. The hierarchy of the architecture is shown in the figure below.

Among them, the cluster decision layer is mainly carried out at the top of UAV cluster, which completes the task decision function of UAV cluster, determines the macro type of tasks and the approximate scale of task subgroup. The task allocation layer is mainly carried out in each task subgroup. According to the task requirements and the status quo of cluster resources, the allocation of task execution units and the construction of cluster subgroups for task execution are completed according to the allocation principle of maximizing task efficiency. The flight path planning layer is mainly carried out in each cluster sub-group, which can be calculated by one or several UAVs in the group according to the scale of the sub-group, complete the planning of the cooperative flight path of each platform in the cluster sub-group, and provide the desired trajectory for the formation to execute the task. The formation control layer is also carried out in each cluster group. The flight control quantity of the platform is obtained by calculation, and the cluster formation is controlled to patrol along the corresponding desired flight track, and the formation formation is maintained.

The design of dynamic multi-level distributed cluster management and control architecture can effectively solve the complexity of large-scale cluster node cluster management and control. At the same time, it can make the UAV cluster quickly obtain global battlefield information, improve the management efficiency of UAV cluster for individual configuration tasks and behaviors, and has strong adaptability to battlefield changes.

4 Task-Oriented UAV Cluster Hierarchical Networking Communication Architecture

The task-oriented hierarchical network communication architecture of UAV cluster is adopted for the characteristics of UAV cluster network scale, fast change of network topology and big difference of node speed domain.

Network The communication system consists of a backbone network and subnets. Command centers/AWacs and relay weapons form the backbone network; The other weapons are divided into multiple clusters, each cluster as a subnet, the number of members in the cluster is not less than 8, each cluster based on the corresponding protocol to select the cluster head and sub-cluster head from the cluster members, sub-cluster head and cluster members have the same function, as the first alternative when the cluster head is off the network, accept the responsibility transfer of the cluster head at any time. Backbone nodes are responsible for relay information transmission, network maintenance, topology control, and information exchange and sharing between clusters. Cluster heads are mainly responsible for subnetwork maintenance and centralized processing of services within clusters.

For UAV cluster task, the network communication requirements and technical characteristics are analyzed, which are divided into four application modes: large-scale, high bandwidth, fast response and interference degradation.

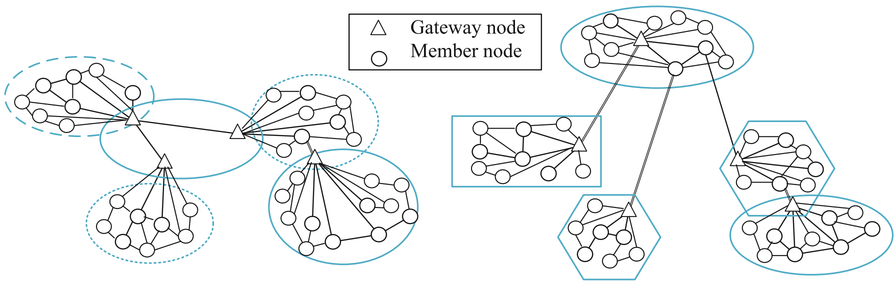

Fig. 3. Schematic diagram of large-scale network mode, time-sharing hierarchical topology (left), and frequency division hierarchical topology (right).

4.1 Large-Scale Network Model

For UAV cluster aerial assembly, dense penetration, formation recovery and other tasks, the network communication requirements are large number of network nodes, strong resistance to destruction, high connectivity between nodes, and relatively small end-to-end business volume.

The large-scale network mode adopts hierarchical clustering network architecture. According to the network scale, network topology change, node speed domain, space domain, function domain difference, the whole network is logically divided into multiple clusters, each cluster contains a number of nodes, one of which is the cluster head node, the rest are common member nodes. Compared with the centralized network, the hierarchical clustering network architecture can reduce the network maintenance scope to a single cluster and reduce the resource scheduling overhead. Compared with the fully distributed network, the pathfinding broadcast range is concentrated among cluster heads, which can reduce the pathfinding consumption and provide the possibility to increase the network scale requirements. According to the electromagnetic environment and specific task requirements, the hierarchical clustering network structure can be designed into time-sharing hierarchical topology and frequency hierarchical topology, as shown in the following figure. It is easy to realize the information interaction between clusters in the time-sharing and hierarchical topology design, and the end-to-end throughput is small. The frequency division topology achieves higher device cost in exchange for efficient information interaction between clusters and higher end-to-end throughput.

Hierarchical cluster network architecture uses cluster heads to manage the whole network in a hierarchical manner, reducing control signaling and enhancing the reliability of information transmission. The architecture can accommodate a large number of nodes, strong destruction resistance, high connectivity between nodes, and efficiently and reliably adapt to the network requirements of UAV cluster large-scale flying formation tasks such as air assembly, dense penetration, formation recovery, etc.

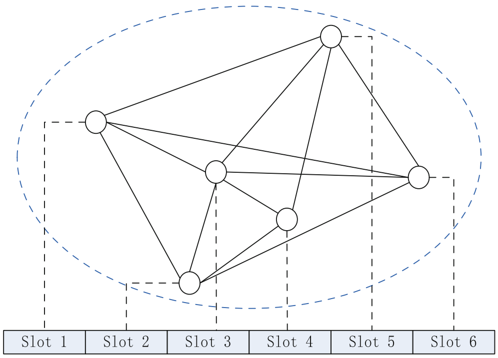

Fig. 4. Schematic diagram of fast response network mode

4.2 Quick Response Network Mode

For UAV cluster cooperative positioning and attack guidance tasks, the network requirements are high end-to-end interaction frequency and demanding delay, but the number of network nodes is small.

Fast response network adopts time-sharing and distributed architecture. In this architecture, all nodes are equal, and there is no need to set the center point of the network, so the network overhead is low. At the same time, time-sharing system ensures the network response speed and avoids data collision. Nodes and neighbors can apply for and authorize resources based on service types. The network architecture has a flexible topology, which enables elastic network extension, ensures local fast response performance optimization, improves communication frequency, and reduces network delay. The time-sharing and distributed architecture is shown in the Fig. 4.

In time-sharing and distributed architecture, communication resources of each node are allocated according to time slots, which minimizes information redundancy and collision and improves information response speed. The architecture has high interaction frequency between nodes, small end-to-end delay, and efficiently and reliably meets the network requirements of high-frequency interaction tasks of UAV clusters, such as collaborative positioning and guided strike.

4.3 High-Bandwidth Network Mode

For UAV cluster situation construction, wide area search, target recognition, evaluation and other tasks, the network requirements are large end-to-end communication bandwidth, but the number of network nodes is small, and the communication delay is not sensitive.

High bandwidth network adopts frequency division distributed architecture. This architecture does not require the network to set the center point, the network overhead is small, and the frequency division system ensures the network bandwidth is sufficient. The collision backoff algorithm is used to optimize the performance of local high bandwidth without affecting network services. It is suitable for reducing delay sensitivity and improving end-to-end throughput.

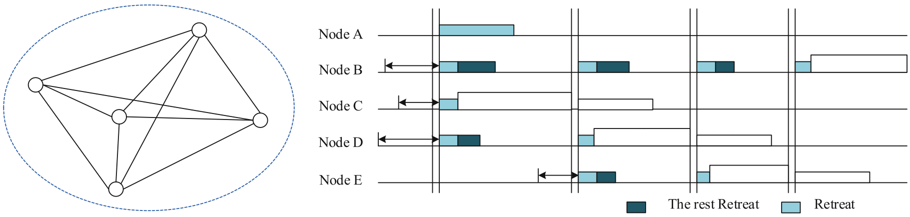

Fig. 5. Schematic diagram of high bandwidth network mode

In the frequency division distributed architecture, resources of each node are allocated according to demand, and the size of the competition window is adjusted by design to maximize the end-to-end throughput of the network. The architecture has large end-to-end communication bandwidth and is insensitive to communication delay. It can reliably meet the network requirements of UAV cluster image transmission tasks, such as situation construction, wide area search, target recognition, and evaluation.

4.4 Interference De-escalation Network Mode

When the UAV cluster communication environment changes and encounters enemy interference, the communication network switches to the interference degradation mode. In this mode, high-bandwidth and low-delay services are suspended, and adaptive sub-carrier deduction technology is adopted to ensure the highly reliable transmission of basic interactive information of weapon cluster.

According to the random fluctuation of channel response caused by frequency selective channel or certain interference, the communication frequency band is divided into multiple segments, and then whether to continue to use it is selected according to the quality of its transmitted data, so as to reduce the influence caused by channel and interference. Assuming that the random fluctuation of the channel has uneven influence on the transmitted signal frequency band, in the signal sender, the signal communication frequency band is divided into N equal parts before normal data transmission. According to the quality of each equal part recorded by the channel quality detection module, whether to use this frequency segment for the next data transmission is decided. If this frequency segment is used, the actual data delivered at the data link layer is transmitted on this frequency segment. If this frequency segment is not used, the populated data stored at the physical layer is transmitted on this frequency segment. In the signal receiver, the receiving node records the receiving quality of the transmitted data in each frequency segment, and then takes out the actual data from all frequency segments for demodulation and decoding according to the frequency band negotiated with the transmitter, discarding the filled data, so as to achieve the anti-interference effect in the frequency domain. The workflow of interference degradation mode is shown in the Fig. 6.

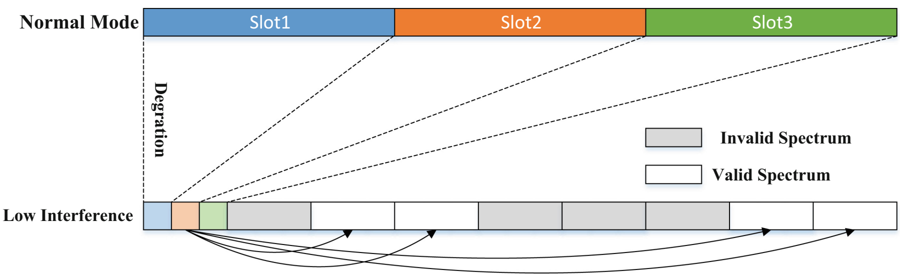

Fig. 6. Workflow of interference degraded working mode

5 Conclusion

Based on the unmanned aerial vehicle of the complexity of the cluster analysis, based on task, the cluster control behavior and information interaction model, the complex system elements, the interaction between the collection, complex rule set, complex feature set as a coordination task subsystem, cluster control subsystem, communication subsystem for the network architecture backbone architecture layers, And completed a variety of models, multi-level, multi-type sub member of the architectural layer, comprehensive build a can not only the overall task oriented, and can adapt to the need of the local task, can be based on the global and local based architecture, both can rapid response, and can avoid the complex unmanned aerial vehicle cluster system architecture of conflict collaborative decision-making and implementation.

According to different task requirements, unmanned aerial vehicles based on hierarchical cluster complex system architecture design, from the collaborative task, cluster control, network communication system analysis and design from three aspects including task oriented unmanned aerial vehicle hierarchical cluster collaborative task structure and behavior model, hierarchical cluster model and hierarchical control architecture and network communication behavior type structure and behavior model.

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