The Architecture Design of A UUV Swarm System Based on Distributed Operation Theory

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***Abstract*—In order to improve the anti-submarine warfare capability, an anti-submarine UUV swarm system based on distributed operation theory is proposed. This paper describes the basic concept of the distributed operation theory and the anti-submarine operational mode of the UUV swarm, designs the system architecture, basic composition and control structure of the UUV swarm, and finally describes the operational workflow of the UUV swarm in detail. The proposed system integrates artificial intelligence technology, distributed operation concept and swarm tactics, which can effectively promote the diversification of the underwater battlefield awareness and the systematization of anti-submarine warfare so as to improve the naval cooperative anti-submarine warfare effectiveness and undersea control capability.**

Keywords-UUV (unmanned underwater vehicles) swarm; swarm intelligence; cooperative anti-submarine; distributed operation

I. INTRODUCTION

In recent years, unmanned weapons have emerged on the battlefield with some success, and unmanned combat technology has become an important development tendency of military science and technology. With the development of artificial intelligence and swarm technology, unmanned swarm warfare has made great progress and will become a research hotspot of future wars. It also will be applied to future systematic warfare. Unmanned swarm warfare will open a new mode of modern warfare, and at the same time, it will expand to underwater battlefield and become the new normal of future maritime anti-submarine warfare.

At present, many countries have carried out researches on UUV swarm operation. The United States takes UUV swarm operation very seriously, U.S. Naval Postgraduate School proposed an advanced undersea warfare systems as early as 2011 [1], U.S. Defense Science Board has launched an outlook on next-generation unmanned undersea systems in 2016 [2], U.S. Department of Defense has designed the unmanned systems roadmap in 2007 and 2013 respectively [3] [4]. Recently, the research on UUV swarm mainly focuses on navigation and positioning, formation control, path planning, mission planning and so on. Reference [5] introduces the development of the UUV swarm projects in military and civilian areas, presents domestic and overseas research status and development of the key technologies of UUV swarm. Reference [6] introduces the cooperation method and combat model of MAUVs (Multiple Autonomous Underwater Vehicles) system, presents the problems which MAUVs system has to solve. Reference [7] introduces researches on the formation control method of multi-AUVs on the basis of path following and the formation control method of multi-AUVs on the basis of target tracking. Reference [8] introduces the application of the unmanned system swarm in the marine combat.

Based on the previous researches, this paper applies the distributed operation theory to the design of the UUV swarm anti-submarine warfare system, introduces the system architecture and control structure of the UUV swarm in detail, and describes the basic operational workflow of the UUV swarm cooperative anti-submarine system.

II. THEORY OF DISTRIBUTED ANTI-SUBMARINE OPERATION

The concept of Distributed operation was first proposed by U.S. Naval War College in 2014, whose connotation was to decompose the capabilities of the traditional large-scale multi-functional combat platform into a large number of low-cost small combat platforms with relatively single function. These small combat platforms cooperate with each other and perform specific missions in the form of swarm so as to play the advantage of systematic warfare. It can reduce the complexity of the platform, lower the combat costs, and improve flexibility of the operational organization.

As soon as the concept of distributed operation was put forward, the U.S. army attached great importance to it. In recent years, the U.S. army explored the key technologies and implementation of distributed operation actively and carried out some researches and practices in the battlefields of sea, air and space. The U.S. Navy has elevated distributed operation to the core operational concept of seizing sea control in the strategic document "Surface Force Strategy-Return to Sea Control".

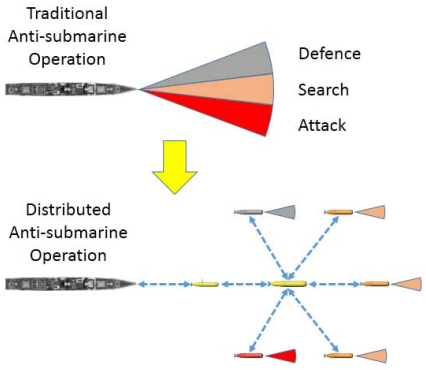

Figure 1. The concept map of the distributed anti-submarine operation

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With the rapid development of information technology and intelligent underwater robots, it provides the technical basis for the distributed operation theory to extend to the underwater battlefield, and the distributed anti-submarine operation will become an important development tendency of underwater warfare in the future. As shown in figure 1, distributed anti-submarine operation changes the traditional anti-submarine combat mode that large multi-functional warship performs mission independently, distributes the capabilities of large warship to a large number of anti-submarine UUVs. The UUVs work together to complete specific anti-submarine mission in the mode of human intervention combat or independent combat with the support of anti-submarine warfare system.

As shown in table I, distributed anti-submarine operation realizes cooperative anti-submarine warfare with large scale UUV swarm and distributed operation ability. It has the characteristics of good robustness and short development cycle. It can lower the cost and realize higher operational flexibility, play the advantage of anti-submarine warfare system, and improve the efficiency of the anti-submarine warfare.

TABLE I. CONTRAST BETWEEN TRADITIONAL ANTI-SUBMARINE OPERATION AND DISTRIBUTED ANTI-SUBMARINE OPERATION

Traditional Anti-submarine Operation	**Distributed Anti-submarine Operation**
Platform Operation	System Operation
Complicated Organization	Flexible Organization
Centralized Functionality	Distributed Functionality
Limited and Costly Platforms	Numerous and Low-Cost Platforms
Vulnerable to Contermeasure	Robust to Contermeasures
Multi-Decade Development Cycles	Rapid Development Cycles

III. THE ARCHITECTURE DESIGN OF THE UUV SWARM

A. The Anti-Submarine Operational Mode of The UUV Swarm

The UUV swarm is an important part of distributed anti-submarine operation system. It consists of a number of UUVs with different functions, which are able to conduct anti-submarine operation independently or cooperatively. Based on anti-submarine operational network, the UUV swarm integrates the advantages of unmanned combat technology and swarm tactical to realize the intelligence, cooperativeness, flexibility and diversity of underwater unmanned anti-submarine warfare.

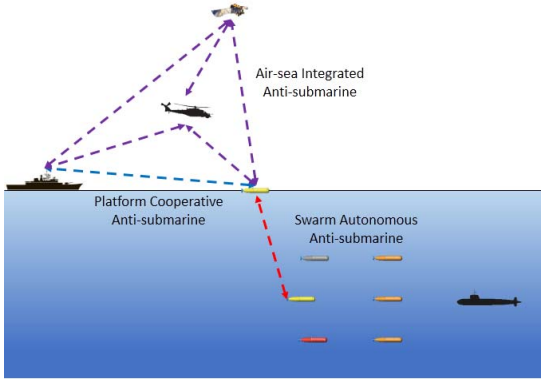

Figure 2. The anti-submarine operational mode of the UUV swarm

As shown in figure 2, the UUV swarm can conduct anti-submarine operation autonomously with the supported of artificial intelligence technology through autonomous organization and independent decision. It can also be used, in the case of human intervention, as an important underwater node of the warship's anti-submarine system to implement platform cooperative anti-submarine warfare. And it can also be used as an important underwater node of air-sea integrated anti-submarine warfare system to build integrated and stereo anti-submarine warfare network and realize stereo anti-submarine warfare.

B. The Architecture Design of The UUV Swarm

The UUV swarm realizes distributed anti-submarine operation and swarm operation with the support of key technologies such as distributed computing, swarm intelligence, path planning, mission planning, data fusion, etc. As shown in Figure 3, according to the actual requirements of anti-submarine operation, the architecture of the UUV swarm system is divided into five layers, namely, the operational resource layer, the operational management layer, the operational capability layer, the operational application layer and the cooperative operational application layer.

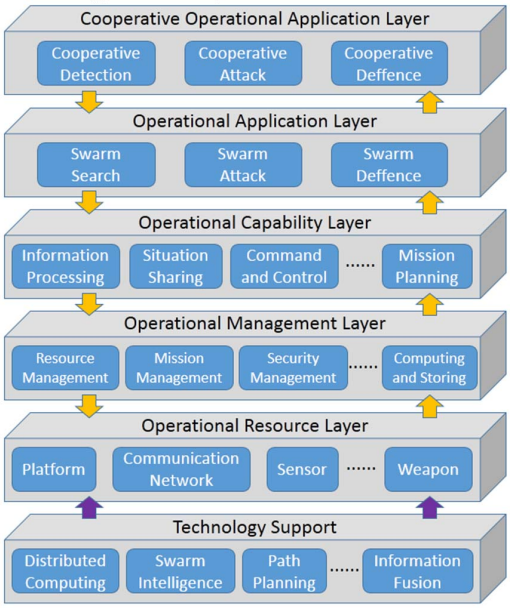

Figure 3. The architecture of the UUV swarm system

Based on the operational capability of the existing anti-submarine system, the UUV swarm distributes anti-submarine operational resources such as sensors, weapons, communication equipment and computer storage equipment on different anti-submarine combat platforms, and forms an efficient anti-submarine operational network by using the underwater acoustic communication equipment.

According to the instructions and internal anti-submarine strategy, through distributed computing management technology, the system conducts the anti-submarine operational management, including resource management, mission management, system security management, tactical computing and storing, etc., so as to realize efficient dynamic resource management, flexible

anti-submarine tactical cooperation and real-time anti-submarine tactical calculation. And it enables the system to have the operational capabilities such as real-time data processing, battlefield situational awareness and sharing, cooperative command and control and flexible operational mission planning, etc., providing basic guarantee for carrying out anti-submarine warfare missions. Under the unified scheduling and control of the swarm intelligent technology, the distributed UUVs can verify, judge and cooperate with each other, completing swarm detection, swarm attack and swarm defense against the submarine. It can also participate in the platform cooperative anti-submarine warfare and air-sea integrated anti-submarine warfare, so as to realize cooperative search, cooperative attack and cooperative defense.

C. The Control Structure Design of The UUV Swarm

Based on the requirement of the distributed anti-submarine operation and the functional characteristics of the UUV swarm, the UUV swarm is divided into four subgroups according to the functional integration: command subgroup, detection subgroup, attack subgroup and defense subgroup, as shown in Figure 4.

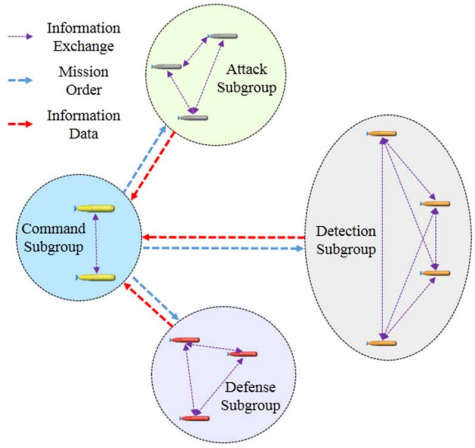

Figure 4. Multi-layer distributed control structure of the UUV swarm

The operational nodes of each subgroup are divided into command UUV node, search UUV node, attack UUV node and defense UUV node according to their functions and missions. The communication UUV node is added when the UUV swarm conducts cooperative anti-submarine mission with warship. Each UUV node of each subgroup adopts modular design and assembly. Task modules can be installed selectively according to the type of anti-submarine combat tasks, and one or more task modules can be configured according to the carrying capacity of platforms.

The operational nodes of the UUV swarm constitute a complex distributed anti-submarine warfare network. In order to optimize, allocate and coordinate these operational resources, a reasonable control structure of anti-submarine system should be built. The UUV swarm adopts different control structure according to the combat task and swarm composition, mainly including centralized model, distributed model and multi-layer distributed model.

The multi-layer distribution model integrates the characteristics and advantages of the centralized model and the distributed model, which not only benefits global anti-submarine cooperation, but also considers computing ability, communication ability, swarm robustness and survivability comprehensively. Considering the characteristics of slow underwater acoustics communication rate, narrow bandwidth and swarm function distribution, it is not suitable to adopt distributed structure completely for large-scale underwater swarm. Therefore, the UUV swarm adopts multi-layer distributed control structure, as shown in Figure 4. The UUV swarm adopts the multi-layer distributed execution framework including core decision layer (command subgroup), distributed cooperation layer (detection subgroup, attack subgroup and defense subgroup) and task execution layer (individual UUV).

The control structure of the system is divided into two levels. In the view of the whole system, the system adopts a centralized control structure. As the control center, the command subgroup is responsible for the anti-submarine command, control and decision of the entire UUV swarm. Subordinate to the command subgroup, other subgroups exchange information with the command subgroup and perform specific combat tasks. In the view of subsystems, each subgroup presents a distributed structure. Individual UUVs complete the overall combat tasks of the subgroup through communication and cooperation under the same combat objectives.

This kind of multi-layer distributed control structure can adapt to the underwater combat environment better, whose advantages are as follow:

1) It can effectively reduce the communication amount between command subgroups and each subgroup, and it adapts to the combat environment better under the condition of insufficient underwater acoustic communication capability

2) It can reduce the complexity of task assignment algorithm and the time and resource consumption between command subgroups and each subgroup.

3) The system has strong robustness. When one member of the subgroup fails, other members of the subgroup can take over and complete its combat task, and the failure of a subgroup does not affect the normal work of other subgroups.

IV. ANTI-SUBMARINE WARFARE FLOW OF THE UUV SWARM

A. Typical Attack Flow of The UUV Swarm

As shown in Figure5, the anti-submarine warfare flow chart of the UUV swarm is presented. When performing the anti-submarine warfare mission, the command subgroup begins path planning and formation control according to preset battle plan or operational instructions given by manned operational platform, so as to form unmanned underwater anti-submarine formation. And then the UUV swarm carries out mission planning according to operational mission, generates operational plans, and sends operational instructions to the subgroups. After the detection subgroup receives the detecting order, the anti-submarine cooperative detection is carried out, and each individual in the detection subgroup sends the detection information to the command subgroup in real time. Command subgroup carries out information fusion and data synthesis for the detected information to generate and

share battlefield situation information relying on its powerful ability of data analysis and processing. Once the submarine target is detected and identified by the detection subgroup, the command subgroup makes command decisions based on artificial intelligence, implements the calculation of target motion element and fire allocation, generates attack plan, and issues attack order and attack plan to the attack subgroup. After receiving the attack order, the attack subgroup will allocate the fire resources, and launch the combat payload to attack the submarine when the attack conditions are reached. During the attack process, the detection subgroup carries out detection and tracking on the submarine continuously, evaluates the attack effect, the command subgroup updates the battlefield situation and decides to attack again if needed based on the detection information and the attack effect.

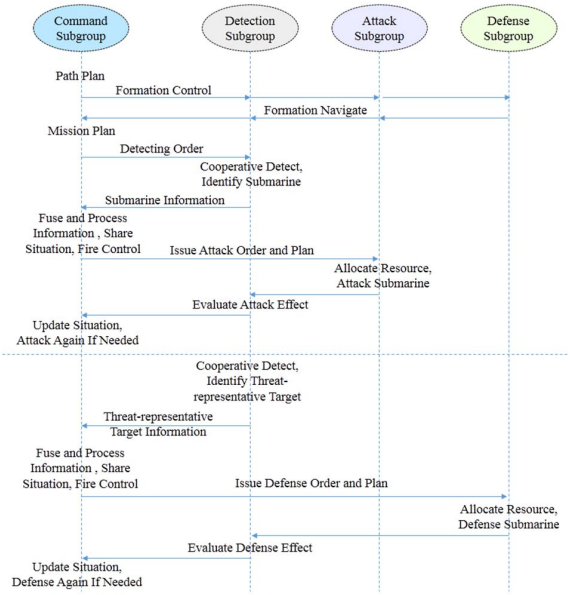

Figure 5. The anti-submarine warfare flow chart of the UUV swarm

B. Typical Defense Flow of The UUV Swarm

Once detecting and identifying the threat weapons such as torpedoes launched by enemy submarine, the detection subgroup reports to the command subgroup. The command subgroup makes threat alert and command decision immediately, implements the calculation of the motion element of the dangerous target and fire allocation, generates defense plan, and issues defense order and defense plan to the defense subgroup. After receiving the defense order, the defense subgroup will allocate the fire resource, and launch the defense weapons. During the defense process, the detection subgroup carries out detection and tracking on the submarine and the dangerous target continuously, evaluates the defense effect. On the basis of the detection information and the defense effect, the command subgroup updates the battlefield situation and decides to defense again if needed.

V. CONCLUSION

This paper proposes an anti-submarine UUV swarm system based on distributed combat theory. The system has the following advantages:

Adopting modular and distributed structure design, the UUV swarm can select the task module for each UUV and the size for each functional subgroup according to the combat task, and can configure one or more task modules according to the carrying capacity. It makes the organization of the UUV swarm more flexible and more adaptable.

The multi-layer distributed control structure can realize the centralized command, distributed control, decentralized execution and cooperative anti-submarine. It makes the operational organization and implementation more flexible.

Through artificial intelligence technology, swarm information interaction and distribution calculation, it is more conducive to give play to the advantage of swarm intelligence. According to the change of underwater battlefield situation, the UUV swarm can adjust the anti-submarine strategy in time, optimize the allocation of combat resources and adapt to the complex, dynamic and changeable anti-submarine combat environment.

In the future, with the rapid development of Internet of things, information technology and artificial intelligence, key technologies such as UUV communication, navigation and positioning, operational planning， formation control and intelligent swarm application will become more and more mature. UUV swarm will certainly become an important combat force in the underwater battlefield and play an important role in anti-submarine warfare in the future.

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