To cite this article：SUN N, MA S S. Key technologies and combat pattern analysis of autonomous flight sonobuoy [J/OL]. Chinese Journal of Ship Research, 2021, 16(6). http://www.ship-research.com/EN/Y2021/V16/I6/109.

DOI: 10.19693/j.issn.1673-3185. 02096

Key technologies and combat pattern analysis of autonomous flight sonobuoy

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Abstract: Launched from a sonobuoy tube and capable of autonomous flight, the autonomous flight sonobuoy frees the traditional sonobuoy from dependence on costly aerial delivery platforms. It can be installed on various small- and medium-sized surface ships and unmanned boats to support the operational needs of long-distance and rapid situation awareness regarding underwater battlefields. By outlining the current development of the tube-launched technology for the unmanned aerial vehicles (UAVs) and the sonobuoy technologies, this paper tends to offer insights into design of autonomous flight sonobuoys and summarizes the key technologies for autonomous flight sonobuoy swarm operations, including swarm control, swarm intelligent decision-making, and networked detection. Furthermore, the combat patterns of autonomous flight sonobuoy swarms in wide-area coordinated detection, multi-source information support, and assistance with combat effectiveness evaluation are analyzed. The results can provide references for the demonstration, design, and application of autonomous flight sonobuoy swarms.

Key words: autonomous flight sonobuoy; unmanned swarm operation; combat pattern; intelligence

CIC number: U666.7；E925.4

0 Introduction

Modern submarines are becoming increasingly difficult to detect due to the sustainable development and improvement of relevant technologies, such as vibration and noise reduction, anechoic tile, and demagnetization. Boasting fast delivery, broad coverage, high-efficiency of submarine searching and low exposure to the detection and attack from underwater submarines, etc., aerial delivery of sonobuoys is one of the best countermeasures against anti-submarine detection at the moment. For this reason, the deployment of anti-submarine warfare (ASW) helicopters, along with aerial delivery of sonobuoys, has become an effective means for modern surface ships to expand the detection range in ASW and enhance their ASW capability. ASW helicopter, as a major kind of sonobuoy delivery system, however, strict standards are required regarding the store-space aboard the ship and relevant maintenance support, disqualifying small and medium-sized surface ships from carrying such helicopters for long- and medium-range sonobuoy delivery and limiting the application of conventional sonobuoys. This is especially true for new-type combat platforms such as unmanned vehicles.

As the quantity of combat units represents a more important determinant of the outcome of a war than their capability [1], decomposing an expensive multi-mission weapon system with highly integrated functions into some low-cost small-scale combat platforms can well improve the cost-effectiveness of operations in future underwater warfare (UWW). Besides, thanks to the rapid development of the unmanned aerial vehicle (UAV) miniaturization technology, particularly the tube-launched UAV, there are chances for sonobuoys now to move away from reliance on costly aerial delivery platforms and fulfill the mission of medium- and long-range deployment in a more independent, flexible, and intelligent manner. By fusion of the existing underwater detection and the UAV miniaturization technology, the so-called sonobuoy featured by tube-launch and autonomous flight becomes more

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Received：2020－08－29 **Accepted**：2021－01－14

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efficient with less energy-consumption and boasts intelligent networking, swarm control, and wide-area coverage. Compared with sonobuoys in the traditional mode of carrying and deployment with airborne platforms, autonomous flight sonobuoys demonstrate wide-ranging adaptability to surface platforms and environment, especially for carry and use massively on various surface combat platforms. Furthermore, in future UWW, autonomous flight sonobuoys have a broad application prospect in that they can support surface ships to carry out fast wide-area underwater detection at a lower cost.

This paper puts forward overall design approaches for autonomous flight sonobuoys and a swarm combat pattern. For this purpose, the current development of tube-launched UAV and sonobuoy technologies is outlined, and the design approaches for autonomous flight sonobuoys are presented. Then, key technologies for swarm operation of autonomous flight sonobuoys are summarized, and the concept of such swarm operation and the typical combat pattern are analyzed.

1 Development status of technology

1.1 Tube-launched UAVs

Miniaturization has long been one of the pursuits of UAVs, and tube-launched UAVs represent exactly a major result of this commitment. It enables UAV transport and deployment with diverse airborne and shipborne platforms. Featured by low cost and flexible transport and deployment, tube-launched UAVs adapt to various missions as required. In particular, it can properly replace the traditional larger and more expensive platforms in operations including battlefield surveillance and reconnaissance under hostile high-risk conditions, which helps steer clear of any potential danger to platform safety. Therefore, it sees a broad application prospect. Countries such as the United States, Italy, and Israel carried out a wide range of demonstration, development, and test verification of tube-launched UAV [2] and brought forth some representative products presented in Fig. 1 [3], with their specific features described as follows:

Coyote, developed by Advanced Ceramic Technology (America), is one of the most successful tube-launched UAVs for sonobuoys [4]. Weighing about 5.44−6.35 kg and having a wingspan of about 1.47 m, it can be contained in a standard Class-A sonobuoy launcher. And it boasts a maximum speed of 85 knots, a cruising speed of 60 knots, and an endurance of 90 min.


(a) UAV Coyote (b) UAV Cutlass


(c) UAV Horus (d) UAV SkyLite

Fig. 1 Foreign products of tube-launched UAV [3]

Cutlass, developed by L-3 Unmanned Systems (America), adopts a general-purpose sonobuoy tube for the launch from an air- or ground-based system, with its navigation system available for real-time control by the corresponding ground station [5]. With a weight of about 5.44 kg, a wingspan of about 1.4 m, a maximum speed of 75 knots, and a cruising speed of 55−60 knots, it reports an endurance of up to 40−60 min thanks to its power from lithium batteries.

Horus, developed by OTO Melara (Italy), can fly autonomously (or fly under ground-based control) after its launch from a manual catapult or a 120 mm launch canister. It weighs about 2 kg and has a length of about 0.98 m. Adopting a canard wing layout with a wingspan of 1.65 m, it reports a cruising speed of 31 knots, a sprinting speed of 58 knots, and an endurance of 60 min.

Skylite A, a canister launched drone developed by Rafael (Israel), it adopts foldable wing and X-shaped tail wing. With a weight of about 6.02 kg and a wingspan of about 1.5 m, it boasts a cruising speed of 37−55 knots and an endurance of 90 min. SkyLite B, as the latest variant, is featured by more excellent flight performance and endurance [6].

As tube-launched UAV becomes a proven technology, many small-type UAVs with improved design have adapted to the launch from inside the sonobuoy tube, which means increasingly broad prospects.

1.2 Sonobuoy

Sonobuoy is designed to detect underwater targets as a kind of buoy-type underwater sound remote-sensing device. Since its introduction in the early 1940s, sonobuoys have had a profound influence on anti-submarine operations after long-term advances. Fig. 2 presents a series of typical sonobuoys.

Fig. 2 U.S. military sonobuoys

Cylindrical in appearance, a sonobuoy is equipped with separable vanes and antenna dome on the top and foldable umbrella antenna, ultra-high-frequency (UHF) radio transmitter, acoustic signal amplifier, sonar array, battery, and self-sinking device inside the cylindrical shell. Different in specific functions, sonobuoys are classified into about twenty types. Specifically, they can be divided into active and passive sonobuoys by detection mode, and directional and omnidirectional ones by target location mode. Hence come omnidirectional passive buoys, directional passive buoys, omnidirectional active buoys, directional active buoys, temperature-depth buoys, extended echo ranging buoys, communication buoys, etc.

Three groups of standard sizes for sonobuoys are gradually established during the long-term development—A, G, and F [7], which are presented in Table 1 in detail.

Table 1 Types and sizes of sonobuoys

Model	Diameter/m	Length/m	Maximum weight/kg
A	0.124	0.914	17.69
G	0.124	0.419	8.16
F	0.124	0.123	5.44

Different types of sonobuoys vary greatly in range coverage. For instance, active sonobuoys generally reach about 1.5 n mile for large- and medium-sized submarines, and the passive ones mostly reach 1−5 n mile for nuclear powered submarines or up to 10 n mile by means of line-spectrum detection. With a maximum working depth of hundreds of meters, sonobuoys can carry out detection across the thermocline. These sonobuoys with different functions play a significant role in modern ASW operation.

The technology of sonobuoy have went through a continuous development process, which the detection mode evolved from passive to active, operating frequency band from high to low frequency, the target localization from omnidirectional to directional, the array quantity from single-array element to multi-array element, the target tracking from single-static to multi-static, and the signal control mode from analog to digital [8]. For instance, adopting multi-static detection, the latest fourth-generation airborne active sonobuoy can fully unleash the strengths of both active and passive detection to improve the detection range and positioning precision by reducing the reverberation interference of active detection through transceriver seperation, increasing the array aperture, and optimizing beam-forming. Hence comes the ability of the sonobuoy to implement real-time multi-target tracking. To well counter underwater threats, sonobuoys will also move towards networked and swarm-oriented applications, thus setting higher standards for the carrying and rapid deployment capacity of relevant platforms.

1.3 Underwater detection by small-type UAVs

BAE Systems is developing a small type of UAV—unmanned targeting air system (UTAS) for the US military that is designed to be launched from the maritime anti-submarine patrol aircraft P-8A Poseidon [9]. Equipped with a magnetic anomaly detector (MAD) similar to that carried by UAV Coyote, this system is designed to detect and locate submarine targets by testing small changes in the magnetic field of the earth after its launch from the P-8A's launch tube.

UTAS makes up for the defect of the P-8A anti-submarine patrol aircraft that it is denied built-in magnetic detectors with a UAV swarm equipped with MADs. It can also provide target-related data

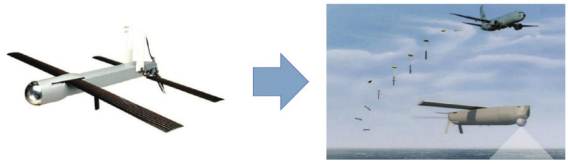


Fig. 3 U.S. military UTAS [9]

for its long-range gliding torpedoes, i.e., high altitude anti-submarine warfare concept (HAAWC) system.

The concept of combining the tube-launched UAV technology with the MAD is of much reference significance to the development of autonomous flight sonobuoys.

2 Key technologies of autonomous flight sonobuoy

2.1 Overall design

Autonomous flight sonobuoy is designed to integrate UAV with the traditional sonobuoy so that it can be placed in the sonobuoy tube and thus enable autonomous flight of a sonobuoy via the tube-launched technology. Component reuse and wing folding & unfolding mechanism make up the critical design requirements of autonomous flight sonobuoys based on the proven technologies of miniaturized UAV and sonobuoy.

In terms of component reuse, as miniaturized UAVs share similarities with sonobuoys in the functions and structures of many components, the number of components can be reduced by reuse design. In general, a small-type UAV system is composed of body structure, avionics, power device, take-off & landing system, etc. Specifically, the body structure is composed of the airframe, wing, etc.; the avionics system is composed of processor, sensor, payload, antenna, battery, etc., and conducts flight control; the power system is composed of power battery, propeller, power motor, etc., and provides the power required for flight; the take-off & landing system is composed of ejection rope, ejection rack, parachute, etc., and ensures take-off and parachuting.

A sonobuoy generally consists of antenna, controller, battery, hydrophone, cable, damper mechanism, deceleration mechanism, floating mechanism, and cylinder [10].

As shown in Fig. 4, components such as antenna, processor, battery, deceleration mechanism, and folding wing of the miniaturized UAV and the sonobuoy in an autonomous flight sonobuoy are well equipped for reuse. Therefore, the equipment complexity can be reduced by the reuse design of the above components for effective control of the volume and cost of the autonomous flight sonobuoy.

For achieving a tube-launched sonobuoy, the autonomous flight sonobuoy uses components such as the pivot mechanism and the torsion spring to ensure inside-the-tube folding and outside-the-tube unfolding of the wings. The pivot mechanism, with proven application in the tube-launched UAV technology, represents an important component for the

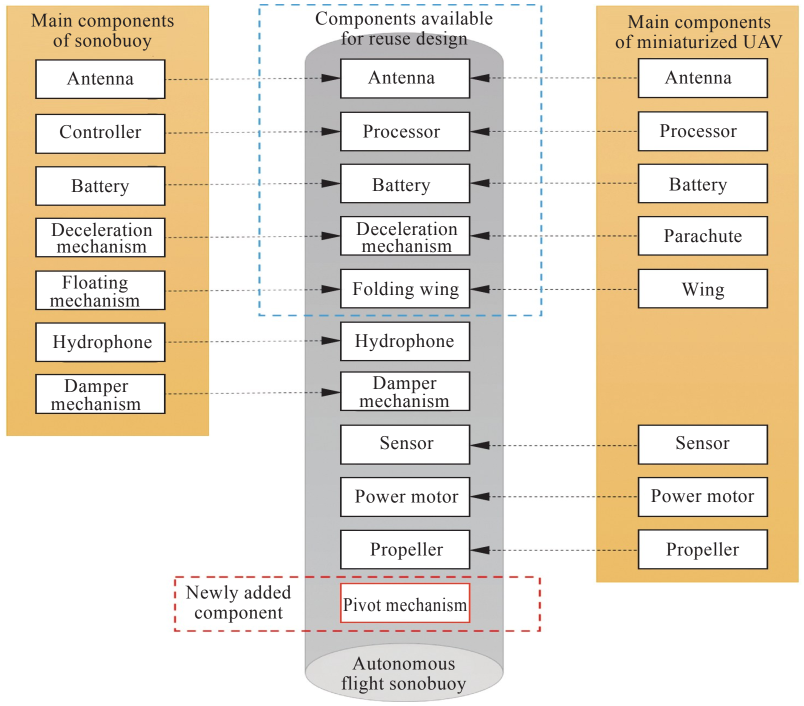


Fig. 4 Components of autonomous flight sonobuoy

tube-launch of an autonomous flight sonobuoy.

Fig. 5 shows a typical small-type pivot mechanism. After the wing runs through the pivot pin via a lug (left or right lug), it is pressed into the corresponding lug through the ball bearing. The structural load is thereby transmitted to the wing. At the end of the pivot pin, a pair of torsion springs are installed to wind and unwind themselves around the pivot pin to ensure the folding and unfolding of the wings[3]. Fig. 6 shows how the wings of the autonomous-flight sonobuoy are launched in the folded form from inside the tube and how the pivot mechanism and the torsion springs complete the process of wing folding, unfolding, and locking.

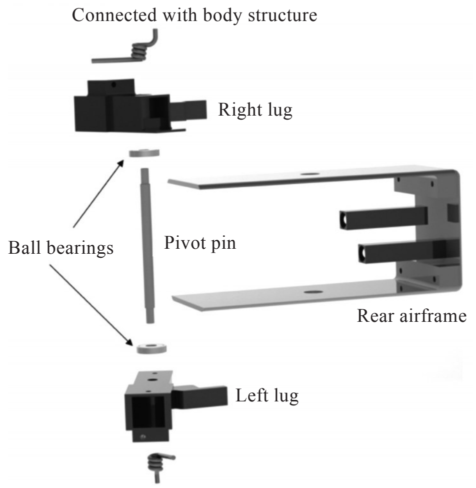
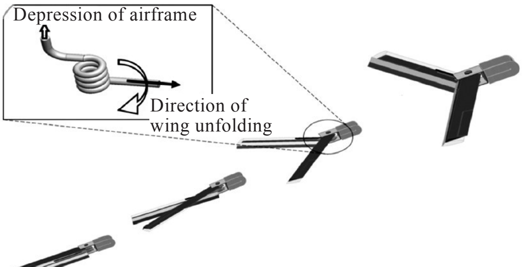
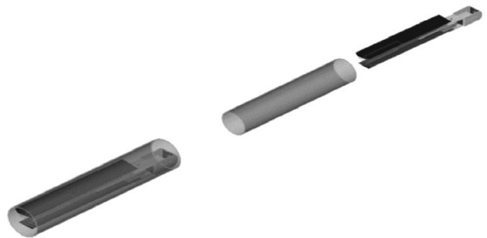


Fig. 5 Structure of pivot mechanism [3]



(a) Wings unfolding, locking, and fastening



(b) Wings are launched in the folded form

Fig. 6 Process of wing folding, unfolding, and locking of autonomous flight sonobuoy [3]

In summary, compared with traditional sonobuoys relying on aerial delivery platforms, autonomous flight sonobuoys can avoid heavy reliance on expensive airborne carrier platforms through tube-launch and autonomous flight. For this reason, it can be stored massively on and delivered independently from various sur-face ships, especially small- and medium-sized surface ships and unmanned surface vehicles unqualified for helicopter take-off and landing. Accordingly, it stands a chance to fully unleash the loading capacity of surface ships and thereby serve the need for continuous delivery of a large number of sonobuoys in relevant operations.

2.2 Key technologies for underwater operations

A single sonobuoy can just perform limited missions in the vast area for an underwater operation. Therefore, autonomous flight sonobuoys are committed to intelligent swarming and self-organized flight and underwater networked detection via swarm control and intelligence technologies. That means taking full advantage of flexible networking, fast deployment, and wide-area coverage of swarms to accomplish complex underwater operations under intense-hostility conditions at the lowest cost. Specifically, swarm control, swarm intelligent decision-making, and underwater networked detection represent the key technologies for swarm operations of autonomous flight sonobuoys.

2.2.1 Swarm control

Swarm control refers to the technology that an unmanned swarm control all the nodes during mission performing and form and maintain some geometric configuration [11] to adapt to platform performance, battlefield environment, tactical missions, etc. To achieve wide-area coverage in the relevant seas for operation, the operation swarm composed of a large number of autonomous flight sonobuoys is required to support the configuration optimization of space, time, and communication topology and switch between formations through shrinking, expansion, and rotation. In the case of any increase or decrease in mission nodes or target adjustment, dynamic adjustment, avoidance, and reconstruction can be performed via swarm control.

Methods applicable to swarm control include the behavior control method, navigation-following method, virtual navigation method, etc. [12]. Specifically, the navigation-following method [13], as a relatively proven one, involves identifying a navigator in an autonomous flight sonobuoy swarm, with other sonobuoys as followers who calculate their relative positions to the navigator and follow its movement, to ensure effective swarm control. For this method, the navigator may become the weak link of the swarm—once it fails, the whole swarm may get out of control, which, however, can be well offset by the alternative navigation strategy.

2.2.2 Swarm intelligent decision-making

The swarm intelligent decision-making of autonomous flight sonobuoys represents the key to the supremacy in underwater operations, as it helps increase the survivability of the overall system to battlefields featuring intense hostility: in the case of possible loss of some operation nodes, it can still ensure the smooth completion of the relevant operation (s).

Involving many aspects such as environment perception, threat judgment, track planning, and dynamic allocation and scheduling of missions[14], swarm intelligent decision-making is all about the following two aspects. One is ensuring the dynamic allocation and conflict resolution of missions among multiple nodes according to the principles of maximum profit-loss ratio and task balance to avoid conflicts in the utilization of single-node resources. The other is maximizing the number of missions accomplished or minimizing the time spent in the mission performing on the precondition of the best overall efficiency of the swarm to fully unleash the strengths of coordinated operation of the swarm.

The algorithms for swarm intelligent decision-making to ensure dynamic mission allocation mainly include the ant colony algorithm [15], particle swarm optimization algorithm, genetic algorithm, and market auction algorithm[16]. Amid dynamic external uncertainties, an autonomous flight sonobuoy swarm can carry out underwater operations in an efficient and proper manner by designing and adopting proven algorithms in the face of emergencies such as unexpected mission-related targets, threats and environment, node damage, and change of swarm size to maximize the operational effectiveness.

2.2.3 Underwater networked detection

Featuring remarkably long duration and narrow bandwidth, underwater acoustic channel reports a low rate of underwater acoustic data transmission. Besides, due to the environmental noise from ships, activities of marine life, wind, waves, etc., signal attenuation and transmission losses are significant, which greatly increases the likelihood of data loss and bit error of communication. Moreover, noise, temperature fluctuation, and serious multipath attenuation also affect the underwater network communication link[17]. An autonomous flight sonobuoy swarm can convert the underwater detection information acquired by the buoys into radio signals for cross-domain communication. With technologies of data transmission, information distribution management, and coordinated processing decision-making support, such a swarm can also ensure fast and accurate interaction between the information of all nodes via a stable wireless communication link, thereby overcoming the low rate and poor stability of underwater communication. With the above technologies, an autonomous flight sonobuoy swarm can carry out wide-area underwater networked detection and self-restoration in the case of a node failure to build its solid area-wide perception of the underwater battlefield and ensure the interactive sharing and integration of the information on underwater operations.

2.2.4 Return of underwater detection data

As autonomous flight sonobuoy is equipped for wireless data reception & transmission and communication relay, a swarm composed of many such sonobuoys is available for coordinated use. To be specific, the sonobuoys set as the detection nodes are designed to detect underwater the relevant targets, and those set as the communication relay nodes conduct continuous flight over the detection area. The underwater detection data acquired by the detection nodes are received through radio communication and then returned to the surface ships via relay communication.

3 Analysis of combat pattern of autonomous flight sonobuoy swarm

Autonomous flight sonobuoy swarm, as a kind of intelligent unmanned system equipped for fast delivery in its very nature, serves to form remotely underwater sensor coverage areas for warships and perceive relevant targets beyond the threats from enemy submarines and launch attacks with weapons. Compared with traditional sonobuoys that rely on costly airborne platforms for delivery, autonomous flight sonobuoy swarm is suitable for various small- and medium-sized surface ships and unmanned boats and supports decentralized storage and multi-mission deployment. It is thus consistent with the concept of distributed underwater operation in the future.

Fig. 7 shows the concept of the swarm operation of autonomous flight sonobuoys. In this concept design, an autonomous flight sonobuoy swarm can accomplish diverse missions of an operation, such as area-wide coordinated detection, multi-source information support, and assistance with operation effect evaluation under complex underwater conditions and brings stronger battlefield survivability to its own side while posing greater challenges to the enemy's response efforts.

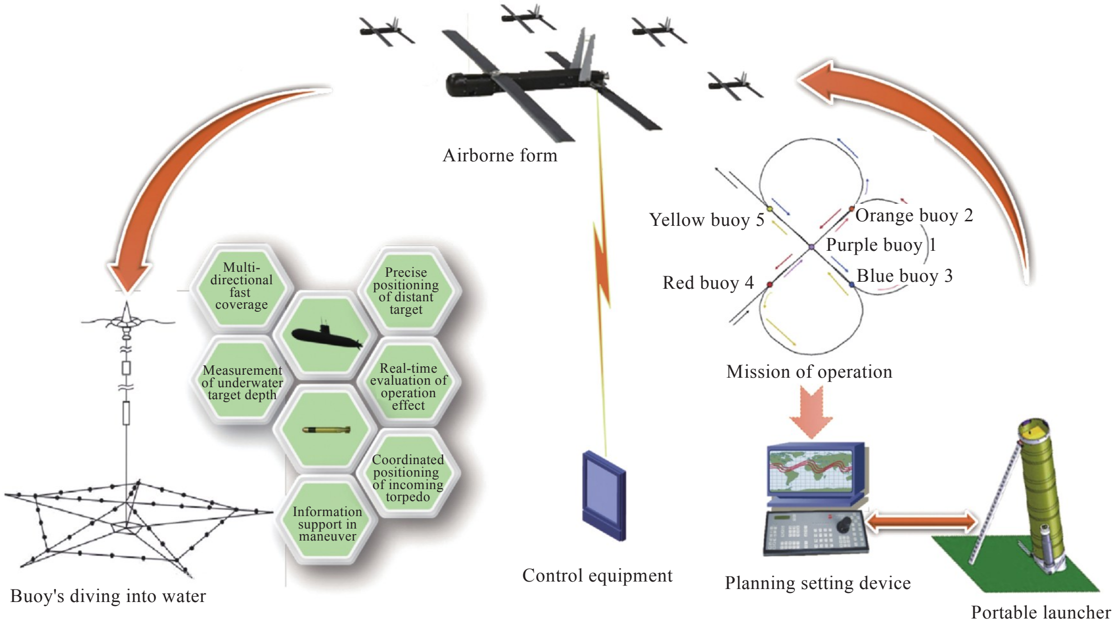


Fig. 7 Concept of swarm operation of autonomous flight sonobuoys

3.1 Area-wide coordinated detection

In carrying out the missions of an anti-submarine operation, surface ships generally need to remotely detect and locate underwater targets in the relevant seas for operation beyond the threats from enemy submarines to ensure information support for underwater operations. In complex underwater operation conditions and broad anti-submarine mission areas, however, surface ships generally meet the following challenges:

1) Subject to the detection range of the sensor, the sonar equipment on the relevant ship alone cannot maintain the perception of underwater targets in more distant areas.

2) Due to factors such as sea conditions, range of helicopter, maneuverability, load, and departure time interval, it is difficult for ship-based helicopters to keep relevant operations for a long hang time.

3) The limited number of platform-based anti-submarine helicopters fails to enable the simultaneous response to multi-directional threats from distant underwater targets.

An autonomous flight sonobuoy swarm is one of the best solutions to the above problems. When equipped with a large number of autonomous flight sonobuoys, surface ships can easily break through the limited range of their sensors, thereby achieving remote detection of underwater targets. Besides, such ships also manage to provide a good solution to the insufficient number and short loiter time of ship-based helicopters. They are equipped for the fast delivery of sonobuoys to many operation areas at all times amid uncertainties of a battlefield to ensure area-wide coverage and coordinated detection. This means taking full advantage of the superiority of a buoy swarm in numbers and thereby significantly enhancing the continuous perception of underwater targets in distant operation areas.

3.2 Multi-source information support

Effectively launching attacks on underwater targets depends on precise target-related information support. However, surface ships report more significant errors in the detection of distant underwater targets with their self-contained sonar equipment and can hardly measure the depths of the targets, which directly weakens the attack capability against such targets. With the advantages of fast delivery and close observation, an autonomous flight sonobuoy swarm can significantly reduce detection error and improve its precision, thereby providing ships with more precise information on underwater targets. Besides, laying multiple groups of hydrophone arrays at different depths for vertical multi-static detection, vertical linear array sonobuoy can also obtain and estimate the depths of the relevant targets. It follows that precise information support on the depths of underwater targets contributes to much stronger attack effectiveness of underwater weapons.

As to underwater defense, although evasive maneuvers of surface ships represent one of the most preferred countermeasures for commanders against the threat of incoming torpedoes, this process can greatly lower the detection effect of the torpedo alarm sonar and also leave commanders in the dilemma of many choices. An example choice is one among maintaining continuous tracking, conducting evasive maneuvers after precise interception, and carrying out well-timed interception after immediate evasive maneuvers. For the above cases, an autonomous flight sonobuoy can solve the conflict between the carrier ship's maneuvers and continuous detection facing the commander and maintain the capability of continuous detection of the relevant targets during the maneuvers. In this way, such sonobuoys not only ease the pressure on the commander for decision-making but also ensure the real-time availability of information support for multi-echelon interception. It follows that an autonomous flight sonobuoy swarm that ensures diverse target information support will become a significant player in future underwater defense operations.

3.3 Assistance with operation effect evaluation

Surface ships need to conduct real-time operation effect evaluation of underwater operations and decide whether to launch a second attack accordingly. In the absence of information support, however, commanders have trouble observing and testing the operation effect, with evaluation results hardly reliable. Nevertheless, independent information support for the operation effect can be provided by planning the routes of autonomous flight sonobuoys, taking full advantage of their characteristic fast deployment and close detection, tracking synchronously the after-launch trajectories of underwater weapons, and carrying out close tests of the explosion area after the weapon attack.

4 Conclusions

Boasting high platform adaptability, autonomous flight sonobuoys can be loaded on a large number of small- and medium-sized surface vessels and unmanned boats unequipped to carry anti-submarine helicopters as an alternative product to anti-submarine helicopters to conduct diverse missions of an operation such as underwater search, detection, and effect evaluation and thereby enhance the perception of underwater battlefield.

Autonomous flight sonobuoys can serve diverse operation needs. For instance, temperature-depth gradient measurement buoys and environmental noise measurement buoys can be delivered to measure information on the hydrological environment in an anti-submarine area. Active sound-source buoys can be deployed to ensure extended echo ranging. Many problems still face autonomous flight sonobuoys in swarm control, intelligent decision-making, and manned/unmanned coordination at the moment. Nevertheless, challenges are also accompanied by opportunities, as autonomous flight sonobuoy swarms can adapt to future maritime operations, meet the future trend towards distributed underwater operations, and make some difference to the patterns of underwater operations. Therefore, it enjoys a broad prospect. The results of this study can help surface ships overcome their inadequate capability of remote underwater target detection and perception.

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自主飞行声呐浮标关键技术及作战样式分析

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摘　要: 自主飞行声呐浮标是一种能够在管内发射并具备自主飞行能力的声呐浮标,其使传统声呐浮标摆脱了对造价高昂的空中投送平台的依赖,可适装于各类中小型水面舰艇、无人艇平台,并满足对水下战场态势远距离快速感知的作战需求。介绍无人机管内发射技术和声呐浮标技术的发展现状,提出自主飞行声呐浮标的设计思路,总结自主飞行声呐浮标集群作战的关键技术,包括集群控制、集群智能决策、组网探测等,分析自主飞行声呐浮标集群在广域协同探测、多源信息保障、辅助作战效能评估等方面的作战样式,结果可为自主飞行声呐浮标集群的论证、设计、应用提供借鉴。

关键词: 自主飞行声呐浮标; 无人集群作战; 作战样式; 智能化