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CMSI Translations #3: Discussion on the Requirements and Methods of Intelligent Decision-Making in Torpedo Attacks by Unmanned Underwater Vehicles

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翻译

TRANSLATIONS

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Discussion on the Requirements and Methods of Intelligent Decision-Making in Torpedo Attacks by Unmanned Underwater Vehicles[1]

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Abstract

Autonomous technology in unmanned equipment is currently the most dynamic frontier technology field, and improving the level of intelligent decision-making is an inevitable trend in the development of unmanned underwater vehicles (UUVs). Torpedo attack decision-making is an important part of attack-type UUVs' attack missions, and it is also the basis and premise for forming self-organizing cross-domain collaboration, autonomous cluster confrontation, and other operational capabilities. Beginning by sorting through the characteristics of operational use and typical mission styles, this article summarizes the advantages and disadvantages of UUVs compared to manned platforms, analyzes the decision-making content different from traditional torpedo attacks, expounds on the key issues that need to be resolved in implementing decision-making functions, and, based on the development status of machine learning technology, proposes an intelligent decision-making method suitable for solving problems such as large uncertainty in observation data, difficulty in guaranteeing real-time attack decision-making, and weak model perception interaction capabilities. This research can serve as a reference for future research in unmanned equipment development and intelligent decision-making fields.

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Introduction

With the rapid development of equipment technology and military applications, unmanned underwater vehicles (UUVs) have become an important part of underwater offense and defense systems, and are pushing the development of underwater warfare from being human-led to a combination of human and unmanned. From the perspective of combat concepts, new styles of warfare such as unmanned system cluster warfare and cross-domain collaborative warfare have

[1] 马亮 [Ma Liang], 郭力强 [Guo Liqiang], 张会 [Zhang Hui], 杨静 [Yang Jing], and 刘剑 [Liu Jian], 无人水下航行器鱼雷攻击智能决策需求与方法探讨 ["Discussion on the Requirements and Methods of Intelligent Decision-Making in Torpedo Attacks by Unmanned Underwater Vehicles"], 水下无人系统学报 [*Journal of Unmanned Undersea Systems*], vol. 31, no. 2 (April 2023), pp. 323-327.

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emerged. From the perspective of combat missions, the mission field of unmanned platforms has begun to expand from support to main combat. From the perspective of operational entities, unmanned platforms are gradually replacing some manned platforms as important forces impacting war. As an American think tank pointed out in a research report entitled "The Emerging Era in Undersea Warfare," the future style of underwater warfare will develop towards the systematization of submarines/unmanned platforms, and submarines need to gradually transform from front-line tactical platforms similar to aircraft to collaborative platforms similar to aircraft carriers.[3]

Autonomous technology in unmanned equipment is currently the most dynamic frontier technology field, and improving the level of intelligence in decision-making is an inevitable trend in the development of UUVs. Torpedo attack decision-making is an important part of UUVs' attack missions, and it is also the premise and foundation for unmanned equipment to form self-organizing cross-domain collaboration, autonomous cluster confrontation, and other operational capabilities. The torpedo attack decision-making of weaponized UUVs needs to be completed autonomously by the platform, which poses a series of new challenges and demands for its behavior modeling and intelligent decision-making methods. If the methods of manned platform torpedo attack decision-making are still used, the combat potential of unmanned platforms cannot be fully utilized. Therefore, it is urgent to study the intelligent decision-making methods that can meet its torpedo attack decision-making needs based on the operational characteristics and mission styles of UUV equipment, focusing on the special underwater battlefield environment.

1 Operational Characteristics and Tasks

Currently active military UUVs are mainly large or ultra-large platforms, such as the "Poseidon" dual-mode UUV, "Manta" giant UUV, "Killer Whale" ultra-large UUV, etc. These types of vehicles generally have a displacement of no less than 5 tons, superb self-sustainment capabilities, and high degree of autonomy, and can flexibly configure sensors and mission modules. They possess advanced operational capabilities such as payload delivery, intelligence collection, mine countermeasures, acoustic deception, alert monitoring, anti-submarine tracking, support, and intelligent attack.

Compared to manned platforms, UUVs can take advantage of their wide operational range, flexible use, strong covert penetration ability, relatively low production costs, and small usage risk, etc. With the support of underwater operational information networks, individually or in clusters and in integrated use with manned underwater platforms, they can achieve effective control of important underwater areas such as source waters (*yuantou*), near seas, and near coast.

1.1 Source Waters Strikes

With regards to carrying out attacks on submarines leaving port in source waters that are difficult for manned platforms to reach, multiple different types of UUVs can be formed into a mobile

[3] **Translator's note**: The authors are referring to Bryan Clark, "The Emerging Era in Undersea Warfare," Center for Strategic and Budgetary Assessments, 22 January 2015, https://csbaonline.org/research/publications/undersea-warfare.

underwater unmanned swarm, they can navigate to the vicinity of the opponent's port base according to the planned route, and the reconnaissance-type UUV group will go out to conduct situational reconnaissance. After getting a good handle on enemy submarine movements, the target information is fed back to a command-type UUV or shore-based command center. The UUV group can use underwater acoustic communication or covertly float up to use satellite communication, and, according to the instructions of the command-type UUV or shore-based command center, carry out autonomous multi-directional attacks on the target.

1.2 Ambush in Near Seas Waters

In areas of near seas where submarine activity is dense, stealth standby or mobile searches can be conducted, waiting for opportunities to launch surprise attacks or guide other forces to strike from a distance. Near important waterways where it is known the opposing side may maneuver, multiple UUVs can be pre-deployed at designated positions on the waterway by a mother ship to lie in wait or maneuver and search. UUVs can cruise at a certain depth at low speed, periodically surfacing for positioning, transmitting information, and receiving instructions, or they can autonomously search and detect along a planned route. After discovering a target, they can autonomously attack on command, or they can guide the mother ship or other underwater forces to carry out firepower attacks through information transmission.

1.3 Near-Coast Vigilance

Carry out regular vigilance missions in important port bases and waterways and surrounding sea areas with fixed underwater listening devices in coastal waters, enhancing near-coastal waters defensive operational capabilities. Enemy high-performance submarines and UUVs may be covertly deployed in coastal waters for a long time, attempting to detect, search, and track outgoing vessels. Multiple UUVs can be used for long-duration autonomous underwater patrols, forming a mobile detection network with fixed underwater listening devices, creating a threat denial area with a certain width and depth, striking or effectively delaying enemy underwater forces, preventing their reconnaissance and sabotage actions, and improving the efficiency of anti-submarine vigilance in near-coast waters.

2 Changes in Decision-Making Content for Torpedo Attacks

Traditional torpedo attack decision-making includes aspects such as attack methods, types of torpedoes and guidance methods, and firing positions and positioning plans, and involves necessary prerequisites such as judging the nature of the target, battlefield situation perception, sea area intelligence acquisition, and target motion element calculation. Through the analysis of the operational characteristics and anti-submarine mission styles of UUVs, it can be seen that compared to manned platforms, UUVs have obvious advantages in concealment, flexibility, and operational risk, while at the same time there are gaps in detection capabilities, quantity of

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payload carried, and command and control. This has led to some new changes in the content and related aspects of UUV torpedo attack decision-making.

2.1 Attack Methods

Manned platforms usually categorize torpedo attacks into two categories based on the degree of tactical urgency: normal attacks and emergency attacks. Generally speaking, when the target is judged to be relatively close and poses a high threat to the platform, it is necessary to shorten the weapon launch preparation time, use an emergency attack method at the expense of reducing the accuracy of the target motion element calculation, and implement evasive maneuvers as necessary. Conversely, if the target is far away or not enough to pose a threat to the submarine, a normal attack method is used to accurately judge and observe necessary conditions such as target type and target motion trend, and occupy advantageous launch positions for weapon launch.

For UUVs, due to their relatively low cost and low risk in combat use, the main operational styles are positional ambush (*zhendi fuji*) and mobile patrol (*jidong xunjian*). Under normal circumstances, the target threat level and tactical urgency are not high, so the normal attack mode should be primarily chosen for the selection of attack methods, in order to make full preparation for effective torpedo attack.

2.2 Types of Torpedoes and Guidance Methods

For manned platforms carrying various types of torpedoes, in order to select the type of torpedo and guidance method, it is common to judge the nature of the target and the battlefield situation, and comprehensively analyze the combat technical performance, guidance methods, and operational usage methods and conditions of the torpedoes loaded on the platform.

UUVs are relatively small in size and have limited detection capabilities. Current technology struggles to control wire-guided torpedoes in the same way as manned platforms. Therefore, in executing anti-submarine attack missions, high-performance acoustic homing torpedoes that can implement both active and passive guidance should be chosen as the main type and guidance method. The simultaneous firing of two torpedoes can increase the probability of torpedo hits.

2.3 Firing Positions

The selection of firing positions is key to torpedo attack decision-making. The selection of firing positions for manned platforms is usually constrained by the following three factors: first, feasibility for the platform to occupy the position; second, the probability of hitting a target with a torpedo fired from the occupied position should be as high as possible; third, the probability of being discovered during the positioning process should be as low as possible. Under certain enemy-versus-friendly status and platform maneuverability conditions, the feasible area for torpedo firing, the equal hit probability curve, and the target threat range are important indicators for selecting firing positions.

Since UUVs have strong covert penetration capabilities and no obvious tactical significance for defensive operations, there is no need to overestimate the issue of the platform being discovered by targets. Thus it has a larger position decision-making space, and can even track the target to carry out close-range firing. The selection of attack positions should be based on achieving the highest torpedo hit probability, highlighting the estimation of attack effects under complex confrontation situations and the optimization of attack plans, to ensure that the torpedo can hit the target at the designated attack position.

2.4 Positioning Plans

For selected firing positions, it is necessary to determine the speed, course, and time for the platform to occupy the firing position. Usually, within the speed range that this platform can adopt, the positioning course and time required for positioning corresponding to different positioning speeds are calculated at certain intervals, and a positioning plan table is made, or the control system calculates and provides a certain designated maneuver speed. If the positioning time difference between each plan is not significant, the plan with a lower positioning speed is selected in principle to ensure the concealment of manned platforms.

Positional maneuvering is a process that needs to be adjusted according to the dynamic changes in the battlefield situation. The traditional method of calculating positioning schemes is for the commander to make real-time adjustments by comprehensively judging the situation with the help of the control system. In the weak underwater communication environment, UUVs cannot rely on human-machine interaction to dynamically adjust the positioning scheme. Therefore, in formulating the positioning scheme, it is necessary to focus on the dynamic adaptability of the planning algorithm.

3 Key Issues in Decision-Making Implementation

As unmanned platforms, UUVs are largely deployed to unknown underwater battlefields to carry out operational missions. This requires UUVs to have the ability to autonomously understand and adapt to complex and uncertain environments, as well as to execute tasks efficiently and reliably. Compared to the air and ground, the marine environment is more complex and changeable. The strategic and dangerous nature of far-seas and deep-sea areas coexist, which puts higher demands on the autonomous decision-making ability of unmanned equipment. Therefore, to ensure the effective implementation of decision-making functions of UUVs in torpedo attacks, the following key issues need to be addressed.

3.1 Data Fusion Processing Issues in Complex Environments

Situational awareness is a necessary capability for UUVs. However, in unknown and complex underwater battlefields, there is some noise and error in the observation and interaction of multi-source information. At the same time, underwater communication has the characteristics of long delay, low bandwidth, and weak connectivity. The transmission efficiency of the communication link of each command node is low, resulting in significant differences in the data type, data structure, data scale, and noise level of the information obtained by the platform. Therefore, in the absence of human intervention, [figuring out] how to extract features from complex data from multiple heterogeneous sources such as underwater acoustics, images, and temperature; achieve consistent representation and fusion of information; and provide necessary support for battlefield situational awareness and subsequent target motion element calculation

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is a prerequisite and major challenge for the realization of torpedo attack decision-making.

3.2 Optimization Problem Solving under Uncertainty and Adversarial Conditions

The decision-making process of UUVs in torpedo attacks is a typical dynamic, multi-constraint, and non-linear complex system, influenced by the uncertainty of hydrological conditions in the sea area, the intensity of the confrontation between the two sides engaged in the contest, and the characteristics of the equipment itself. In this complex system, the temporal evolution of each entity state and element will affect the optimization results, such as the dispersion of targets, countermeasures strategies, and the combat performance of torpedoes. When estimating the probability of torpedo hits, if traditional analytical and simulation methods are still used, as the dimension of parameters and the search space increase, there will inevitably be situations where the solution is time-consuming or even where the solution space does not converge. Therefore, the flexibility and efficiency of the solution algorithm need to be considered.

3.3 Rapid and Efficient Decision-Making Problems with Time-Sensitive Tasks

In its “Autonomy” report, the U.S. Defense Science Board (DSB) stated that a significant feature of autonomy is the ability to optimize its own behavior and complete task strategies in an "objective-oriented" manner in unknown environments. The core of autonomy is decision-making, and the pursuit of "speed" that allows for preemptive action is key. UUV torpedo attacks are a covert and sudden task action. The launch platform needs to make quick and accurate decisions with limited observation information to achieve the purpose of surprise victory. The decision-making methods commonly used by manned platforms, such as fuzzy logic, Venn reasoning, and Bayesian networks, often restrict each other in terms of execution efficiency and credibility, making it difficult to meet the real-time requirements of torpedo attack decision-making in UUV assault missions against submarines.

3.4 Decision-Making Trust Issues in Limited Control Modes

The common weapon control modes for UUVs are semi-autonomous or autonomous. In the semi-autonomous mode, commanders can intervene in the weapon launch process as needed in the control loop, which is the "human-in-the-loop" control method. In the autonomous mode, the weapon launch is completed autonomously by the equipment, and the commander only plays a monitoring role in the control loop, which is the "human-on-the-loop" control method. Regardless of whether it is in semi-autonomous or autonomous mode, the control ability over weapon launching is very limited compared with the "human-in/on-the-loop" and "human-on-the-scene" control methods of manned platforms. Therefore, in the matter of UUV torpedo attack decision-making, handing over authority to the autonomous weapon system is a very serious matter, and it is necessary to ensure the accuracy and trustworthiness of the autonomous decision-making results.

4 Discussion on Applicable Methods

In summary, in order to meet the changes in torpedo attack decision-making content and solve key issues affecting the implementation of decision-making functions, study of intelligent decision-making methods that can autonomously learn from changes in battlefield situations is urgently needed. Existing torpedo attack decisions mostly rely on combat simulation technology, establishing task behavior models of various entities through rule-based methods, and making optimization analysis and decisions based on simulation results. On the one hand, simulation decision-making methods guided by optimization objective functions require high completeness of battlefield temporal data and environmental information, and lack the autonomous ability to dynamically adjust decision-making plans in unknown complex waters. On the other hand, this purely conditional judgment method has limited ability to represent entity behavior, and as the complexity of the battlefield situation increases, the computational workload increases exponentially, making it difficult to describe the complex task behavior of entity forces, resulting in deficiencies in the model's portability, expandability, and reusability.

Machine learning provides a new approach to solving decision-making problems in UUV torpedo attacks. The basic idea of machine learning is to enable machines to gain experience through learning data, to predict unknown events or to draw conclusions; that is, the model has corresponding generalization ability. Deep learning is a machine learning method centered on the study of artificial neural network algorithms. Through multi-layer network structures and non-linear transformations, it forms a high-level representation that discovers distributed features of data. Reinforcement learning is a specific type of machine learning method that maximizes the cumulative reward value obtained by intelligent agents to obtain the optimal strategy of the learning process. Deep reinforcement learning combines deep learning and reinforcement learning, comprehensively utilizing the feature (self-)extraction ability of deep learning and the sequential decision-making ability of reinforcement learning, and is considered to be the representative machine learning method for current breakthroughs in cognitive intelligence. At present, data-driven learning modes are widely used. In terms of intelligent decision-making in unmanned (aerial) vehicle warfare, Han Tong et al. and Pan Yaozong et al. applied reinforcement learning to air combat maneuver decision-making. In the process of dynamic interaction with the external environment, they used trial and error to calculate a relatively optimal air combat maneuver decision sequence, achieving relatively good results.

Addressing the issue of high uncertainty in observational data, the capabilities of deep learning for feature (self-)extraction can be utilized, adopting data compression and preprocessing strategies such as multi-channel convolution, long short-term memory networks, and attention mechanisms to achieve dimensionality reduction fusion and consistent representation processing of multi-source heterogeneous data, providing support for tactical behavior recognition and classification.

Addressing the issue of ensuring real-time decision-making in attacks, we can obtain massive sample data based on underwater offensive and defensive situations through computer simulation and the method of transferring a small amount of weakly-labeled experimental data. This replaces the traditional simulation decision-making method based on multi-entity finite state machine search with an offline learning method driven by a mix of data learning and rule

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deduction. This allows for dynamic data changes to adapt to environmental and task changes, thereby endowing the model with efficient decision-making and online self-learning capabilities.

Addressing the issue of weak model perception interaction capability, we can construct a reinforcement learning multi-agent based on the "perception-adjustment-decision-action" cycle through tactical rule knowledge network transformation, so as to enhance the learning ability of the intelligent agent in the process of interaction and confrontation with the environment, providing a progressive self-updating strategy for the situation rule library, and thus endowing the UUV torpedo attack decision-making with the ability to actively learn and adaptively adjust dynamically.

5 Conclusion

Intelligent decision-making in torpedo attacks has significant research implications for the generation of new-quality underwater combat capabilities. Currently, machine learning is in the stage of developing from "perceptual intelligence" to "cognitive intelligence". Although it is relatively mature in dealing with problems in fields such as data mining and pattern recognition, the state-of-the-art (SOTA) performance in knowledge representation and logical reasoning still has difficulties in reaching the level of engineering application. Therefore, UUV torpedo attack intelligent decision-making requires the joint action of combat simulation technology, heuristic optimization algorithms, and machine learning technology. By fully utilizing the unique multimodal data fusion and general adaptive capabilities of machine learning, it can solve the above key problems and compensate for the shortcomings of traditional simulation decision-making methods in terms of dynamics and flexibility, and jointly serve the development of equipment control systems and software. For the next step, it is suggested to start from specific issues such as tactical situation recognition, effective position decision-making, and position maneuver planning, select key aspects suitable for intelligent decision-making research, and by introducing prior knowledge and task behavior simulation modeling methods, shrink the solution space in advance to improve the convergence efficiency of the intelligent learning model and prevent problems such as gradient disappearance or dimension disaster.