Development status and trend of autonomous operation for unmanned surface vehicle

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ABSTRACT

Autonomous operation for unmanned surface vehicle (USV) is the core competence for USV, and an important mean for unmanned and intelligent operation. USVs can be used for multi-mission, so autonomous operation for USV faces a lot of challenges, such as complex and changeable marine environmental factors, limited means of awareness in sea, low degree of automated operational decisions, difficult integration control of sailing and combat equipment. This study summarizes the development status of autonomous operation for USVs from awareness, decision and control. It addresses the difficult issues and current main technologies of autonomous operation for USVs, and points out the deficiencies of the technologies. Finally, based on the analyses of development status, it addresses the development trend of autonomous operation for USV.

Keywords: Unmanned surface vehicle, autonomous operation, awareness, decision-making, control

1. INTRODUCTION

Due to the outstanding advantages of Unmanned Surface Vehicle (USV) in per-forming high threat and long-term maritime combat tasks, with the development of intelligent technology, USV has gradually become the focus of the development of navies of various countries. USV are versatile at sea and can perform many tasks, such as anti-mine warfare, anti-submarine warfare, maritime security, anti-surface ship warfare, supporting special forces operations, electronic warfare, supporting maritime blockade operations, etc. the key to performing these tasks lies in the autonomous operation capability of USV. Autonomous operation of USV means that USV have autonomous capabilities in awareness, decision-making and control, and can cooperate with manned ships or independently implement various operations at sea.

The main operational modes of autonomous operation of USV include penetration attack, long-term suppression, man-machine cooperation, and cluster operation. The first is penetration attack, which makes use of the better invisibility and mobility of USVs compared with manned ships to approach enemy ships or enter enemy depth to attack in the case of confrontation. The second is long-term suppression, which highlights the advantages of USVs in using without personnel support and sustainable high-intensity work, and long-term monitoring and suppression over a wide area, such as long-term tracking of submarines, long-term patrol, and forming an anti-submarine watch circle around the naval fleet to ensure the underwater safety of the fleet. Third, man-machine cooperation, give full play to their respective advantages and make up for deficiencies, and multi-platform cooperative operations. For example, manned large ships carry multiple USVs, which perform reconnaissance, instruction, and strike tasks under the guidance of manned ships. Fourth, cluster operations, multi USVs sustained multiple means and multi-mode coordinated operations against targets.

The autonomous operation of USV faces many challenges, such as the complex and changeable marine environment, the limited means of marine awareness, the low degree of automation of combat decision-making, and the difficulty of integrated control of navigation and armament. This paper discusses the research status of autonomous operation for USV, and puts forward the main problems and future development direction of unmanned autonomous operation.

2. CURRENT APPLICATION OF AUTONOMOUS OPERATION FOR USV

As countries around the world pay more and more attention to maritime rights and interests, in order to deal with maritime rights and interests disputes, the characteristics of USVs such as low cost, high mobility, good stealth and low personnel requirements have attracted the attention of all countries. The United States, Israel, France, Britain and other

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countries have actively committed themselves to the research and development of autonomous combat technology of USVs and achieved a lot of results, some USVs have been equipped in the navies of various countries. The United States has the Navy with the strongest comprehensive strength in the world, and its autonomous combat level of USV is representative.

In April 2021, the US Navy organized the "unmanned integrated battle problem 21" (UxS IBP 21) military exercise[1-6] on the coast of San Diego, California. This exercise epitomized the US Navy's technological and tactical achievements in unmanned and autonomous operations. Through the application of USVs in this exercise, we can analyse the autonomous operation of USVs in the US Navy. The main purpose of this exercise is to explore the omni-directional application of unmanned systems in the operational scenario, and experimentally verify the operational methods to improve lethality, to integrate the capabilities of unmanned systems into all fields and prove how they can solve the key operational problems of commanders at all levels. The exercise mainly includes: Intelligence/surveillance/reconnaissance, joint sharing of target data and firing missile, manned-unmanned formation joint operation.

The US Navy organized many types of manned ships, USVs, unmanned aerial vehicles and unmanned submarines to participate in the exercise, including the following types of USVs, shown in Table 1:

Table 1. Abilities of USVs in exercise.

Name	Abilities	Performances
Sea hunter; Sea Hawl	For weeks or even months, it can search and track the enemy's conventional submarines at sea. It can also be used for anti-mine and other tasks	42m long, 140t weight, maximum speed 31 kn, 18500 km at cruising speed of 12 kn
MANTAS T38	It can carry out ISR, expeditionary logistics and anti-mine missions. Provide stable and continuous logistics support capability for the Marine Corps.	8-12 ft long, cruise speed 25-40 kn, payload up to 4500 lb, draft 18 ft
LRUSV	It can carry ammunition and carry a variety of payloads to accurately track and destroy sea and land targets in the theater	10m long
ADARO	The rugged, portable class X USV is designed around modular payload capability	3ft long

In the exercise, the exercise items participated by USVs include: In the live firing scene, the target ship is detected by USV borne passive sensor, the target ship information is transmitted to the missile destroyer, and the missile destroyer launches the standard-6 missile to attack the target ship without using the ship's sensor. In the scene of anti- submarine warfare, USVs use the towed sonar array on board to search for underwater threats, continuously track submarines, and share underwater target information with manned ships. USV also participated in intelligence reconnaissance and surveillance scene exercises. In this exercise, as a cooperative sensing means in manned-unmanned fleet, the autonomous operation technology of autonomous navigation, cooperative detection and information sharing has been verified, and tactical actions such as cooperative anti-submarine and cooperative over-horizon strike have been practiced.

In aspect of autonomous striking, two USVs in the "Ghost Fleet Overlord" program led by the office of strategic capabilities under the office of the Secretary of Defence, installed Command and control systems, and payloads of electronic warfare, anti-surface warfare and strike warfare. In September 2021, a SM-6 missile was launched from a modular launcher mounted on one of these USVs.

The US Navy has proposed to deploy 140-240 USVs in the fleet by 2045 for various tasks such as supply, reconnaissance, mine laying, missile strike and so on[7].

Other countries have also developed multi types of USV[8], and the main operational applications are shown in Table 2:

Table 2. Typical USVs in other countries.

Country	Name	Abilities
Israel	Katana	It is equipped with electricity Optical and infrared cameras, advanced radar and weapon systems, and can be used for maritime patrol and warning, enemy and friend target identification, target tracking, intelligence reconnaissance, electronic support, etc.
Israel	Protector	9m long, cruise speed 30kn, payload up to 1000kg. Through its plug and play design, the mission capability is reconfigured to allow the use of various mission modules, such as force protection, anti-terrorism detection and exploration, mine deployment operation (MIW), electronic warfare (EW) and precision strike.
France	FDS-3	8.3m long, cruise speed 12kn, payload up to 6700kg. It can be used for Channel cleaning, port search, etc.
United Kingdom	Pacific 950	Autonomous driving and fighting alone for 10 days, capable of chasing targets at a high speed of 45 knots (83 kilometres per hour), with a maximum driving distance of 300 nautical miles (556 kilometres), etc.
China	JARI-USV	15m long, cruise speed 30kn. It is equipped with ship-to-ship missiles, torpedoes, machine guns and other weapons, and can be used for surface warfare, anti-submarine warfare, reconnaissance, etc.

The navies of all countries are not equipped with massive USVs, and still focus on experimental verification. The equipment and technology related to autonomous operation for USV are in the process of vigorous development, and its combat application mode is still in the process of exploration and verification.

The existing technical difficulties are analysed below to explain the existing solutions and current main problems.

3. TECHNICAL DIFFICULTIES AND CURRENT SITUATION

According to the OODA (observation, orientation, decision, action) theory of operation, the autonomous operation technology of USV mainly uses computer technology, control technology, operation model, etc., analyses and processes the perceived information based on understanding the operation mission and task according to the operation regulations and corresponding regulations, as to form a situation that can be understood by the computer. The action plan is decided based on the situation information, and the operation is carried out according to the action plan control platform, sensors and weapons to realize independent operation. This requires that USV have human like awareness, decision-making and control capabilities, and can ensure the implementation of these capabilities in the whole combat cycle. Its technology can be divided into three categories: awareness, decision-making and control, shown in Figure 1. The following analyses the corresponding technical difficulties and current situation for each category.

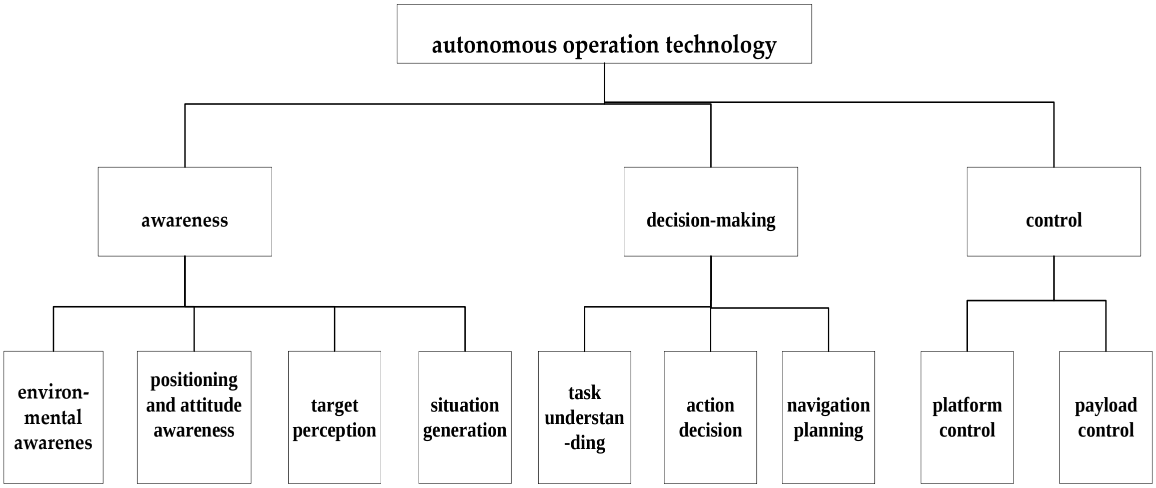

Figure 1. Technical division of autonomous operation for USV.

3.1 Difficulty analysis and current situation of awareness technology

Awareness is the basis of autonomous operation of USV. However, with the expansion of human activities in the ocean and the diversification of operations, maritime awareness is becoming more complex. It is necessary to have stronger robustness and flexibility to support the long-term operation of USV. The USV detects the surrounding environment through the onboard sensor, and analyzes and forms the situation information that can be understood by the computer in combination with the information reported by the shore. USV awareness technology mainly includes environment awareness, positioning and attitude awareness, target awareness and situation generation.

3.1.1 Environment awareness. The complex and changeable marine environment will affect and restrict the use of USV. Fully understanding and mastering the characteristics and change law of marine environment can provide strong support for USV action decision-making and onboard equipment control, and improve the operational efficiency of USV. The main problems and difficulties in being aware of the marine environment[9] are:

- The marine environment is a multi-dimensional complex natural element characteristic environment, which has a variety of environmental forms such as spatial geographical environment, hydrological environment, meteorological environment, physical field environment, underwater acoustic environment, electromagnetic environment and so on. These environmental forms have varying degrees of impact on independent operations.

- The marine environment is affected by many factors. Physically, it is affected by solar radiation, earth rotation and atmospheric circulation. In terms of meteorology, it is affected by factors such as earth surface pressure, temperature, humidity, and precipitation. In terms of geography, it is affected by factors such as seabed topography and the distribution of land and islands around the ocean.

- The marine environment is complex and changeable, with poor stability, uneven distribution of seawater temperature, density and salinity, time-varying seawater flow, fluctuation and sea surface fluctuation, and drastic changes in sea surface weather such as wind, cloud, rain, and fog.

USV mainly rely on onboard equipment to obtain real-time environmental information. For the perception of ocean waves, the radar of the boat can be used to perceive and process the wave height, wave period, waveform, and other information. References[10-13] uses X-band radar to obtain the distribution information of sea surface ocean dynamic parameters in a non-contact manner, based on the resonance effect of radar electromagnetic wave, and specific wavelength ocean surface wave, and the wave direction spectrum information carried by radar echo. For the perception of seawater temperature, density, and salinity, the onboard CTD (conductivity temperature depth) has been relatively mature, which can detect and measure the seawater temperature, conductivity, pressure, and other parameters with a depth of 6000 meters in real time. References[14-17] explores the use of photonic crystal optical fiber and other technologies to test new sensors for detection and measurement. The ship meteorological instrument can continuously measure the meteorological parameters such as wind speed, wind direction, temperature, humidity, air pressure and rainfall in real time[18,19]. For the perception of seawater velocity and flow direction, the seawater velocity vector is obtained by using

Acoustic Doppler velocity profiler (ADCP) based on the Doppler frequency shift of the acoustic signal scattered by particles in the water[20]. References[21-24] study the data processing of ADCP to improve the detection effect of water flow.

For non-real-time environmental information, USV can receive environmental information reported by marine environment observation platform and other detection systems, and obtain meteorological, wave and other environmental information in a large range and for a long time. USV can also obtain fixed environmental information such as islands and water depth in the action sea area by querying the electronic chart.

During the survey mission, USV will carry professional survey loads according to the needs of the mission[25], such as hydrological element survey instrument, shallow layer profiler, forward-looking sonar, long baseline, ultra-short baseline acoustic positioning equipment, optical pump magnetometer, water quality instrument, side scan sonar, multi beam bathymeter, single beam bathymeter, mobile laser scanner, etc.

In general, the range of USV borne equipment to perceive the marine environment is small, the detection accuracy of some parameters is not high, the prediction ability is weak, the control of the equipment in the unmanned state is not perfect, and the ability to process the detection information into environmental products is lacking.

3.1.2 Positioning and attitude awareness. High precision attitude perception and positioning of USV is a prerequisite for USV to complete its tasks such as motion control, battlefield reconnaissance, battlefield support and cooperative operation. Autonomous operation of USV puts forward higher requirements for attitude perception and positioning. In the traditional sense, it is beyond absolute positioning and attitude measurement. It is also required that USV can have the ability of environmental relative position positioning and attitude perception. In general, USV carries out integrated positioning and attitude measurement with the inertial navigation system (INS) and satellite navigation systems, such as Beidou Navigation Satellite System (BDS) and global positioning system (GPS), to obtain the longitude, latitude, speed, heading and other motion information of the USV, as well as the attitude information such as pitch, roll, heave and heading angle.

The main difficulties of USV positioning and attitude perception are: (1) in the case of confrontation, the satellite navigation system is easy to be disturbed and has the problem of failure; (2) When the inertial navigation system works for a long time and is not corrected by other information, the accuracy will gradually deteriorate with time accumulation; (3) Due to the poor stability of the marine environment, the short-term prediction of ship attitude is difficult; (4) The stability problem is solved by the combination of multiple navigation means.

For the failure of satellite navigation system, references[26-30] propose to solve the problem of short-term failure of satellite navigation system by integrating a variety of auxiliary navigation systems, such as Doppler log, magnetometer, barometer, bathymeter, compass, star sensor, radio receiver and infrared sensor. Reference[31] proposed a centralized Kalman filter data fusion method to comprehensively reduce the information of auxiliary visual odometer and intelligent sensor with MEMS inertial navigation system and correct the error of USV navigation system. Visual navigation technology[32-34] uses the method of simultaneous localization and mapping (SLAM) to generate a global map and locate it according to the detection information of optical sensors such as camera and lidar.

For the problem of inertial navigation correction, the inertial navigation system is generally corrected or accuracy evaluated by external reference navigation calibration information. However, in the absence of external accurate information, the correction mainly depends on the real-time dynamic autonomous evaluation of USV. Reference[35] proposed that, without relying on other navigation information, using the equivalent acceleration information of ship inertial navigation and the relationship between inertial navigation velocity error and horizontal attitude angle error, an autonomous evaluation model of inertial navigation horizontal attitude error is established to evaluate and compensate inertial navigation horizontal attitude error.

For the short-term attitude prediction of USV, the main method is to realize the short-term attitude prediction by analysing the ship motion attitude sequence. References[36-39] used LSTM (long- and short-term memory) and SVR (support vector regression) of multi-scale attention mechanism to adaptively predict the pitch, roll and heave of ships online and in real time.

For the stability problem of combined processing of multiple navigation means, the stability problem is mainly solved by filtering. References[40,41] used adaptive interactive multi model filtering algorithm to synthesize various navigation information to solve the instability problem of extended Kalman filtering.

In general, the positioning and attitude perception of USV are relatively mature, and the accuracy and efficiency can meet the requirements of autonomous operation of USV in most cases, but the stability and prediction ability need to be further improved.

3.1.3 Target awareness. USV mainly detect the surrounding water surface, air and underwater targets by optical, electromagnetic, acoustic and other means to provide information support for USV's autonomous combat decision-making and control, which is the key point of autonomous operation. USV is equipped with a variety of sensors to realize the awareness of surrounding targets. The typical sensor configuration is shown in the table below:

Table 3. Methods and characteristics of sensors in USVs.

Types	Methods	Characteristics
Navigation radar	X-band	It can detect sea targets within several kilometers around, has certain detection ability for targets with small RCS, and is vulnerable to rain, fog, sea clutter and so on
Search radar	C/S band, etc.	Detect large RCS sea surface and air targets within the range of more than ten to tens of kilometers. There is a large blind area in the near area, which is vulnerable to rain, fog, sea clutter and so on
Photoelectric tracker	Visible and infrared light	Tracking and ranging specified sea and air targets, with great weather impact
Infrared warning equipment	Infrared light	It monitors the infrared characteristics of surrounding sea and air targets, but does not have ranging capability, which has a great impact on the weather
Camera	Visible light	Monitor the sea and air targets within hundreds of meters around, but it does not have the ranging ability, which has a great impact on the weather
Lidar	Laser	Accurately locate the sea surface target within hundreds of meters around and obtain the three-dimensional information around, which is easy to be blocked and greatly affected by waves
Millimeter wave radar	Millimeter wave band	It has strong penetration ability to fog, smoke and dust, can identify small sea targets, has strong motion detection ability to targets, and the detection distance can be up to several kilometers
Collision avoidance sonar	Acoustics	The accuracy of detecting water surface and underwater targets within hundreds of meters is low
Towed sonar	Acoustics	The accuracy of detecting water surface and underwater targets within several kilometers is low

In terms of the capabilities of various sensors, they all have their own advantages, scope of action and limitations. It is impossible to rely on a single sensor to achieve comprehensive, accurate, and stable detection and tracking of surrounding targets. It is necessary to comprehensively adjust various sensors according to tasks and environmental conditions and certain strategies to complete the awareness of targets.

Generally, for long-distance sea and air targets over several kilometres, it mainly depends on electromagnetic means such as navigation radar and search radar for detection, supplemented by photoelectric and infrared warning equipment for tracking and confirmation. For short-range sea targets, it mainly depends on laser radar and millimetre wave radar for accurate positioning and tracking, and the video images captured by the camera for auxiliary recognition and confirmation. For underwater targets, it mainly depends on acoustic means such as towed sonar and collision avoidance sonar to obtain target characteristics and determine target location.

The main problems and difficulties of target perception are: (1) There are many false targets, so it is difficult to confirm the truly valuable targets. (2) The ocean environment has a great impact, and the sea surface target tracking is unstable. (3) It is difficult to locate and identify small targets at sea. (4) Underwater target extraction is not easy and positioning accuracy is low.

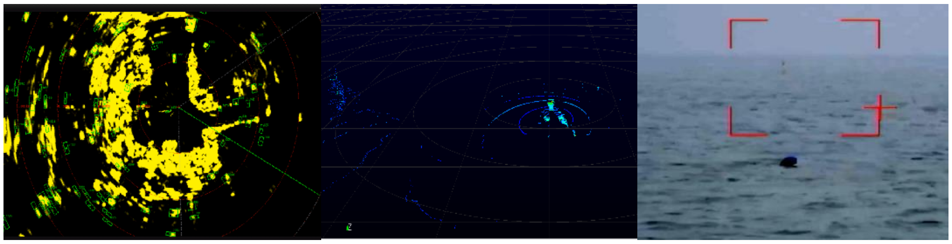
(a) (b) (c)

Figure 2. Awareness problems for USV.

Figure 2a is a typical radar detection echo map. Various ground objects and sea clutter information occupy most of the screen, and most of the radar extraction is false targets, which seriously affects the judgment of USV on the current situation and is difficult to form a reasonable decision.

Figure 2b shows the image detected by lidar. The waves caused by ship motion are obvious in the image, which affects the positioning of the ship and the extraction of targets. Moreover, the change of ship attitude leads to the change of ship point cloud characteristics, which affects the continuous tracking of targets.

Figure 2c is a picture with floating balls and benchmarks on the sea surface. These objects represent that this area is a breeding area. Below the sea surface, there are fishing nets and cultured seafood, and ships are not allowed to enter. Due to the small size of these objects and the small RCS, it is difficult for various radars to detect the target, which can only be identified by video, and there is a lack of corresponding positioning means.

For the problem of false target, a variety of sensor fusion methods are generally used to solve it.

Han et al.[42] proposed the method of fusing the range and azimuth information of pulse radar and lidar, and using extended Kalman filter to obtain speed, heading and other motion information. Gan et al.[43] used Yolo to detect surrounding ship targets and fused multi-sensor data such as camera, radar and AIS to realize vision-based ship environment awareness. Hermann et al.[44] proposed a radar and vision fusion method, which uses statistical and filtering methods to obtain high manoeuvring and fast-moving target information. Liu et al.[45] completed the correlation between lidar clustering, video target detection using SSD network framework, and then spatial and temporal registration. However, for long-range targets, optical means are difficult to achieve, and false targets lack confirmation means.

For the problem of target tracking, radar is traditionally used to track the target, but the target tracking is unstable and easy to be lost due to the environmental impact such as sea clutter. Liu et al.[46] used the amplitude information of sea clutter and target to improve the accuracy of radar target extraction, and proposed a robust multi-Bernoulli filter in K-distributed sea clutter environment to improve the tracking performance of sea multi-target. In terms of visible light tracking, Bu et al.[47] introduced effective convolution operator (ECO) to improve the stability and accuracy of ship target tracking. In terms of infrared tracking, Li et al.[48] filtered the infrared background noise according to the characteristics of complex background and weak morphological characteristics of marine targets, enhanced the target characteristics and improved the tracking accuracy.

For the small target problem, the focus is to separate the target from the background. Callaghan et al.[49] proposed using k-nearest neighbour and support vector machine algorithm to distinguish small targets and sea clutter detected by radar, to improve the probability of detecting and tracking small targets. Zhang et al.[50] used Corner-Net Lite network to visually identify floating targets on the water surface, combined with LIDAR point cloud detection, combined with their confidence to screen and locate floating targets on the water surface.

For the problem of underwater target detection, which is a traditional detection problem, the current research focuses on using new algorithms[51] and artificial intelligence methods[52]. Ali et al.[53] proposed the application of generalized pseudo-Bayesian algorithm to underwater manoeuvring target tracking. Wei et al.[54] applied the particle filter of detection before tracking to the passive target tracking of sonar to improve the detection ability of targets with low signal-to-noise ratio.

In general, at the equipment level, most of the current autonomous sensing devices such as lidar and millimetre wave radar are transplanted from the land, which are greatly affected by the marine environment, far from reaching the nominal performance when used on the land, have weak adaptability to bad sea conditions, and have low detection ability for weak observation targets, so it is difficult to meet the requirements of all-weather and all-weather use. At the algorithm level, there are few training sets for marine targets and their background, and the training data for identifying targets using deep learning method is insufficient, resulting in weak identification ability of marine targets. At the collaborative level, compared with USV, UAV or aircraft has the advantages of wide shooting field of vision and less limited by terrain and other factors, and can perceive the environment or observation objects from multiple directions and angles. Therefore, the collaborative perception of USV and UAV is the development direction of application.

3.1.4. Situation Generation. USV comprehensively senses the environmental information, target information, positioning and attitude information of the craft to form a comprehensive situation, support USV's understanding and analysis of the surrounding environment, and ensure USV's autonomous navigation and autonomous engagement.

The main difficulties of situation generation on USV are: (1) Because the scope of the sea is vast, it is difficult to identify the intention of the sea target. (2) The knowledge representation of maritime situation has not yet been formed, so it is difficult to unify cognition and knowledge reasoning. (3) The marine situation assessment lacks basis and the reliability of the results is low.

For the problem of maritime target intention recognition, the formal plan recognition reasoning model based on logical hypothesis is traditionally adopted. At present, artificial intelligence methods[55-57] such as attention mechanism are gradually used to deal with it. Yang et al.[58] proposed Bayesian intention hierarchical recognition method for air targets in sea battlefield based on relevant characteristic parameters and screening formula of air targets in sea battlefield, which has high recognition efficiency. Liu et al.[59] started from the establishment of a tactical intention reasoning framework based on plan recognition, and used the operational knowledge neural network to explain the enemy's operational process through the acquired target dynamic knowledge. Based on the cyclic neural network, Zhao et al.[60] introduced the attention mechanism into the intention recognition model, distributed and processed the incoming target timing information, and intelligently recognized the target intention.

The problem of knowledge representation of maritime situation is essentially to represent the perceived target, environment, and other information as a computationally processable and formal knowledge entity model, explore and represent the relationship between entities, and provide support for command decision-making. In terms of the concept and framework of situation knowledge, Zhu et al.[61] proposed the conceptual model of situation intelligent cognition and related technical framework. Zhou et al.[62] gave the definition and connotation of intelligence reasoning map, that is, by analysing the relationship between events, such as inheritance and causality, to reveal the evolution law and logic of events and support information interpretation. Wang et al.[63] proposed using scene knowledge atlas to represent the knowledge of joint operation situation. In terms of specific implementation methods, Giovanna et al.[64] proposed learning methods such as fuzzy neural network to solve the problem of multi-agent cooperative situation awareness.

For the problem of maritime situation estimation, it is necessary to evaluate our perception ability from the meteorological, marine environment, electromagnetic environment, and the sensor state of USV, and generate the enemy threat degree based on the reasoning of target position, target attack and defence ability and target intention, to give the comprehensive situation estimation of the enemy and us. Generally, blackboard model, template matching, Bayesian network D-S evidence theory and other methods is used to solve the problem, but the situation uncertainty and fuzziness are difficult to solve due to incomplete data and difficult to predict confrontation behaviour. Li et al.[65] proposed a quantum probabilistic language terminology framework for multi-attribute decision-making, which solves such problems through quantum state, quantum data processing and quantum interaction effect.

In general, the current situation generation of USV mainly adopts general methods, and the research on marine application is not in-depth. There is a lack of corresponding recognition paradigm for the action intention of ships, submarines and underwater frogmen, and there is insufficient theoretical support for the knowledge representation and semantic understanding of USV's maritime situation. Although there are continuous updates of relevant methods such as knowledge atlas, the completeness of maritime situation knowledge representation is poor, the acquisition efficiency is not high, and there are still many difficulties in reasoning methods.

3.2 Difficulty analysis and current situation of decision-making technology

Autonomous decision-making is the core part of autonomous operation of USV. After receiving the task, USV can independently understand the connotation and scope of the task, plan the action plan, form the action sequence, and adjust the action plan in real time according to the emergencies encountered during the execution of the task. The autonomous decision-making of USV can be a part of the process in which people participate, or it can be completely completed by the computer. Technically, it can be divided into three parts: task understanding, action decision-making and route planning. At present, the research on autonomous decision-making of USV at home and abroad mostly focuses on the direction of autonomous navigation planning, and the research results in task understanding and action decision-making are relatively few.

3.2.1 Task understanding. Task understanding mainly refers to the ability to decompose execution steps, make action decision and route planning, and complete more complex tasks through basic task combination in real time and intelligently according to the key words and corresponding contents of the task, intelligently combined with existing combat task examples.

The main difficulties in task understanding are: (1) Combat tasks are generally expressed in natural language, which needs to be transformed into a way that can be understood by computers. There is no complete solution, and its semantic accuracy is difficult to guarantee; (2) The rationality of task decomposition is difficult to determine.

For the problem of task description natural language transformation, the semantic representation of natural language can be transformed based on semantic knowledge base, semantic learning modelling from natural text, and neural network is used for language model modelling. Jackson[66,67] analysed what is the so-called intelligent understanding and representation at the human level, Guo[68] proposed an automatic method for constructing the knowledge base of machine processing. Du et al.[69] used graph convolution network based on syntax type perception for semantic modelling. At present, the research on mission understanding in the field of USV operation is not in-depth.

For the task decomposition problem, the overall task needs to be subdivided into multiple specific, clear, and interrelated subtasks under the constraints of the combat capability and action rules of USV, to facilitate the parallel execution of various equipment and maximize the combat effect. References[70,71] use hierarchical task network to model the task decomposition process and give the decomposition algorithm. Vallon et al.[72] studied the task decomposition method of linear time-varying systems.

The USV task understanding needs to consider the control operation mode, task execution ability, system operation support and other factors, and give a reasonable logical task understanding by analysing the USV state, battlefield situation and combat background. In general, it is still in a relatively primary stage. It can analyse the keywords in the task description and establish relevant relationships, but there is still a lack of in-depth research on its deep-seated semantic information and its relationship with the task background.

3.2.2 Action decision-making. Action decision-making is the key link of USV operation. It refers to determining the execution sequence of tasks and adjusting the specific implementation process of combat tasks according to the current combat task execution and planned tasks. The main difficulties in decision-making of USV are: (1) Abstract modelling of sea battlefield is difficult. The process of naval warfare is very complex, and various elements in multiple domains such as water surface, underwater, air, land and electromagnetic affect and restrict each other. When modelling, it is necessary to abstract various factors on the naval battle field, such as force layout, various interrelations, energy potential, trend direction, operational methods and tactical strategies, weapon use, etc. according to the influence situation, and synthesize them into a variety of combat models oriented to tasks. It is very difficult to achieve correspondence with reality. At present, empirical models are mostly used, which are only applicable to a certain range. (2) The behavioural decision-making is highly confrontational, the decisions of both sides are made at the same time, the non-round game is its typical feature, and the decision-making results affect each other. (3) In the unmanned state, the influence of war fog is further amplified. In the actual naval battle, the lack of information, the consistency of true and false, the change of key information will lead to the significant change of decision-making results, and the commander's command art is difficult to be simulated by computer. (4) The rules of unmanned operation are not perfect, and the opponent will not follow the previous tactical methods. It will often be surprised, various emergencies will appear at any time, and the decision-making response requires high real-time and strong adaptability. (5) The availability of artificial intelligence methods is not high, the training environment is not real, and there are few samples; There are too few real naval warfare samples, and the training samples are often several orders of magnitude worse than the requirements of artificial intelligence. However, if the autonomous learning evolution model is adopted and the self-game is adopted in the environment of small samples or no samples, the modelling is often different from the actual naval warfare, and the effectiveness of the results is often affected.

Sea battlefield modelling has always been the focus of research. For the application of various equipment in different mission modes, a variety of models are designed to cover the combat tasks and scenarios of sea battlefield. Liu et al.[73] analysed the electromagnetic environment characteristics of the sea battlefield for the sea battle scene, and constructed a dynamic electromagnetic environment model integrating sea targets, sea environment, electromagnetic interference, and sensors. According to the characteristics of naval gun firing at sea, Li et al.[74] put forward the decision-making model of naval gun firing at sea.

For the problem of game confrontation, many experts and scholars have put forward solutions based on game theory. In references[75-77], aiming at the lack of dynamics of interference decision-making in electronic countermeasures, a game decision-making model for selecting interference style is proposed; For the problem of decision efficiency. Wonderley et al.[78] proposed to expand the decision criteria of game theory based on the maximum and minimum theorem.

For the problem of lack of information, Liu et al.[79] proposed the solution method of the optimal strategy of the game model under incomplete information. Reference[80-83] proposed to use expert trust network, multi-attribute decision-making, AHP decision-making method of incomplete judgment matrix, active defence strategy selection algorithm and other methods to solve the problem of incomplete information in decision-making, which effectively improves the availability of decision-making.

For the problem of imperfect rules, many studies extract and optimize rules from information by means of rough set, fuzzy set, and decision attribute matrix, and then make decisions under the optimized rules. Liu et al.[84] introduced the improved complete tolerance relation and trapezoidal fuzzy number into the decision rough set, and proposed the three-branch decision-making method and rule extraction of incomplete system combined with Bayes decision-making process. Qian et al.[85] constructed a three-branch decision model and rule acquisition method for incomplete hybrid decision system based on the improved complete tolerance relationship. Ma[86] proposed the extraction method of ship threat measurement rules in incomplete system by studying the strategy generation method under the condition of missing information completion attributes and decision attributes. Wang[87] introduced the conditional attribute matrix and decision attribute matrix under the compatibility relationship, and proposed the rule acquisition algorithm of decision system under incomplete system.

For the availability of artificial intelligence, the current research is mainly from the aspects of artificial intelligence interpretability[88] and generative countermeasure network verification[89], trying to improve the availability of artificial intelligence in military decision-making.

In general, the decision-making of USV is mainly to solve the problems in traditional decision-making. There are still many difficulties to be solved, whether using modelling method or introducing artificial intelligence method. The main problem faced by modelling methods is that it is difficult to evaluate the impact of marine environment on decision-making, while artificial intelligence methods mainly focus on theoretical research and cannot be popularized in practical application because of their great problems in usability.

3.2.3. Route Planning. The route planning of USV is the basis for realizing the autonomous navigation of USV, that is, in the environment with obstacles (ships, reefs, navigation aids, etc.), considering the influence of wave, surge, current and other environmental factors on navigation, planning the navigation route that can safely and effectively perform the task. At present, the main difficulties of navigation planning are: (1) In complex environment, route planning changes greatly due to the low perceived stability and accuracy. (2) The optimization of route planning needs to comprehensively consider many factors such as navigation distance, fuel consumption and equipment application on the basis of task requirements; (3) Route planning requirements can meet the motion characteristics of USV and the impact of marine environment (including wind, wave and current); (4) During daily navigation, we should abide by the international maritime collision avoidance rules and integrate the international maritime collision avoidance rules into route planning and dynamic collision avoidance.

At present, there are many navigation planning algorithms, which can be divided into global navigation planning and local navigation planning from the scope of action. The global navigation path planning methods mainly include visual graph method[90], Voronoi diagram method[91], grid method[92], A * algorithm[93], RRT algorithm[94], particle swarm optimization algorithm[95,96], ant colony algorithm[97], genetic algorithm[98-99], reinforcement learning method[100], etc. Local navigation planning methods mainly include artificial potential field method[01]], dynamic window method[102], speed obstacle method[103]. It can be divided into depth search algorithm, heuristic algorithm and artificial intelligence algorithm.

In general, these algorithms can effectively plan the route reasonably according to the task, avoid collision in the process of execution, and change the route according to the real-time situation, reduce the dependence of USV on personnel to a certain extent, and support USV to have multi task combat capability. However, the problems of stability and environmental adaptability are still prominent. The change of route will lead to the instability of perception and the change of behaviour decision-making, which will affect the autonomous operation process of USV.

3.3 Difficulty analysis and current situation of control technology

The typical characteristic of USV control technology is that it is necessary to implement integrated high-precision real-time control of platform load in unmanned state. The control technology can be divided into two parts: platform control and payload control. At present, the control of USV at home and abroad mostly focuses on the research of platform control, and payload control is mainly a traditional control means.

3.3.1 Platform control. Platform control includes many aspects, such as USV track control, power control, damage management control and so on. The main difficulties are: (1) Under high sea conditions, due to the action of wind, wave and current, the hull response is slow and can not effectively maintain the scheduled route. (2) In the complex environment, the USV moves at a low speed when leaving and berthing autonomously, with great interference from wind, wave and current, and it is difficult to maintain stability in manipulation and control; (3) When various payloads (especially weapon payloads) are used, the power demand changes greatly, and the real-time adjustment efficiency of power supply is low.

For the track tracking problem in high sea conditions, due to the nonlinear characteristics of wind, wave and current, the general method is to comprehensively analyse the influence of wind, wave and current and other environmental factors based on the hydrodynamic model of USV, and design an adaptive platform controller based on the planned route and real-time perception information, which is transformed into the control signal of main engine and steering gear to control the movement of boat in real time. Common methods include PID control, auto disturbance rejection control, fuzzy control, adaptive control, sliding mode control, reinforcement learning control, model free adaptive control and various hybrid control algorithms. Kim et al.[104] proposed a robust synovial control method of disturbance and state observation for the nozzle control of USV water spray system. Literatures[105,106] adopts reinforcement learning method to adaptively control unmanned craft to track path and avoid obstacles dynamically.

For the problem of autonomous departure and berthing, including track planning to reach the berth area, tracking of the planned route and stabilization control to reach the designated position, it is necessary to perform control actions such as deceleration, parking, reversing, parallel berthing, steering, and turning. The following difficulties are solved through comprehensive control: (1) Due to the low speed of USV, the hydrodynamic parameters follow the rudder The disturbance such as jet pump changes greatly. At this time, the motion model of USV is more complex and reflects high-order nonlinearity, so it is difficult to accurately predict the ship motion; (2) When the USV moves in shallow water at medium and low speed, the influence of external factors such as wind, wave and current increases, and the uncertainty of boat motion increases; (3) The configuration and attitude of the ship’s position converging to the desired path are realized under underdrive. In references[107-109], aiming at the nonlinear feedback problem in the process of leaving and berthing, the ship leaving and berthing route is controlled by means of regression neural network and extended dynamic window.

For power real-time control, it mainly includes automatic generation control and power dispatching. References[110-112] study the prediction and control methods of ship power in order to continuously ensure ship propulsion and balanced load use.

In general, there are some solutions to these problems, but they still need to be verified and improved in the actual navigation state, so that they can adapt to a variety of environments.

3.3.2 Payload control. Payload control is mainly used to control various sensors, weapons and communication equipment equipped on USV, as well as various temporary equipment (such as UAV and marine measurement equipment). The main difficulties are: (1) There are many kinds of payloads and different control accuracy. (2) Modularity is a major feature of USV, which should be able to quickly adapt to the changing requirements of various payloads. (3) According to different situations and task requirements, a variety of control strategies are needed to adapt in the unmanned state.

The unmanned payload control method generally adopts the control methods of “man in the loop” and “man in the loop”, combined with the three states of personnel remote control, USV semi autonomy and USV full autonomy to control the payload to varying degrees[113].

At present, the payload control of USV mainly continues the control mode of manned ship, and the research on fully autonomous control mode still needs to be carried out in depth.

4. TECHNOLOGY DEVELOPMENT TREND

In view of the above technical difficulties, combined with the current technical situation, the following development trends are put forward:

4.1 Awareness technology trends

USV autonomous combat perception technology mainly focuses on the development of scene perception, feature level fusion, collaborative detection, and guided tracking:

Scene perception: Fine division of USV combat scenes, and real-time and dynamic management of sensor application according to the use requirements of each scene. For example, USV navigation is divided into inbound and outbound, inshore navigation, narrow waterway navigation and far shore navigation. In the inbound and outbound scene, we focus on using lidar to establish the three-dimensional model of the port area, real-time detect surrounding targets in combination with optical images, and locate targets with high precision. In other navigation scenes, we focus more on using navigation radar and other means, Motion parameters of positioning target and sensing target.

Feature level fusion: The information obtained by optical, electromagnetic, acoustic and other means begins to be fused at the signal feature level, such as radar target extraction, mapping the optical image information with the radar at the point trace acquisition and track initiation, eliminating the false and retaining the true, eliminating most of the information that is not mutually verified, improving the accuracy of perception, and through feature extraction and semantic description, corresponding fusion and tracking are carried out to improve the perception efficiency.

Collaborative detection: Using the detection results of multiple platforms, blind filling, replacement, and accurate guidance can be realized. For example, plan the UAV route according to the perception requirements, control the UAV to detect the targets in relevant areas, and integrate the UAV detection information with the ship detection information to improve the ship’s perception range.

Guided tracking: For the target or target group to be confirmed, target oriented, deploy various means to implement targeted detection and tracking.

4.2 Decision-making technology trends

The autonomous combat decision-making technology of USV mainly focuses on the development of digital twin of scene reconstruction combined with rules, decision-making technology adapted to marine environment, the integration of swarm intelligence and single intelligence, and scalable decision-making framework:

Digital twin of scene reconstruction combined with rules: Scene reconstruction combines regular digital twins to establish a synchronous digital twin system for boat platform, marine environment, and load to assist in training and synchronous decision-making. Monitor each link of USV operation through sensors, obtain detailed data of USV operation and evaluate operation status in real time; The digital image of USV is established as a virtual model, including geometric, physical, behaviour and rule models to describe the physical attributes, geometric parameters, motion characteristics, external driving, and internal perception decision-making control process of unmanned craft. Establish the interaction mechanism between the USV entity and the virtual model, keep them running in parallel, obtain timely and real battlefield data from the actual operation based on knowledge reasoning and game deduction, simulate, and deduce the operation process from the virtual model, intelligently generate and optimize the action plan, to make the factors considered in the operation decision-making more complete, faster response and better plan.

Decision-making technology to adapt to the marine environment: The decision-making technology to adapt to the marine environment integrates the information perceived by the environment into the decision-making, focuses on finely reflecting the prediction of environmental changes into the decision-making, improves the consideration of marine environmental factors in the decision-making, and enhances the adaptability to the environment. For example, put the real-time estimation of wind, wave and current on the sea into the navigation planning, select the optimal way to reduce the impact of the environment on the platform and payload, and maintain the stability of navigation and the availability of payload.

Integration of swarm intelligence and single intelligence: The integration of swarm intelligence and single intelligence combines multi-platform decision-making with single platform decision-making to ensure the consistency and effectiveness of decision-making. For example, the action decision of unmanned craft group and the cooperative action decision of UAV are combined with the intelligent decision of each boat and body through distributed decision-making to improve the decision-making efficiency.

Extensible decision-making framework: The extensible decision-making framework decomposes the task into the combination of meta skills, and improves the adaptability to various tasks through the combination of meta skills. At the same time, combined with the timely intervention of personnel, ensure that the results are available. Taking route planning as an example, the meta skills are divided into point-to-point path planning, target detection, etc. the combination of meta skills supports the execution of basic tasks such as walking through and approaching the target. When performing verification and other tasks, the task is decomposed into multiple basic tasks through reinforcement learning, rule-based planning and other methods, the execution time and parameters of the basic tasks are determined, and the USV automatically performs the meta skills contained in the basic tasks.

4.3 Control technology trends

The autonomous combat control technology of USV mainly focuses on the development of man-machine integrated control, the application of nonlinear uncertain control method and open control architecture:

Man-machine integrated control: First, the commander can remotely control USV, so that the support personnel can intervene in various actions of USV at any time to ensure that the commander has the final control right. Second, reduce the control details of commanders, improve the control efficiency, and reduce the impact of personnel errors on USVs. Third, improve the availability of autonomous control, and personnel do not need long-term monitoring.

Appling nonlinear uncertain control method: According to the nonlinear variation characteristics of wind, wave and current, the nonlinear uncertain control method is applied to solve the problem of response delay of feedback control for hull and payload, and the intelligent comprehensive control method is adopted to improve the control accuracy, stability, and robustness.

Open control architecture: The open control architecture, through robust control design, carries out tolerance design for the uncertainty of the control object, so that the system can maintain or expand the ability of the system when the control object and control accuracy change, adapt to the control requirements of the platform and load in the performance change, support the modular replacement of equipment, improve the system integration ability, shorten the system R & D cycle and save system maintenance cost.

5. CONCLUSION

Driven by emerging technologies such as artificial intelligence, big data, and the Internet of things, with the gradual popularization and application of new combat concepts such as mosaic warfare and decision-making center warfare, USV autonomous operation will become an important part of Marine Intelligent combat.

With the advent of the intelligent age and the development of military civilization, human life, as a non-renewable resource of war, has a higher and higher status. Unmanned war has quietly become an important model of future war. By the middle of this century, key technologies such as multi-sensor intelligent sensing and information fusion, remote information transmission and system integration, and new materials will become more and more mature. USV is expected to change the mode of future naval warfare and become a subversive weapon for future sea power competition.

Starting from the analysis of the application of USV autonomous operation at home and abroad, this paper discusses the difficult problems related to USV autonomous operation. This paper expounds the main solutions to the problems in perception, decision-making and control in autonomous operation and the current research status, summarizes some deficiencies in the current research, points out the development trend of autonomous operation, and puts forward a digital twin and scalable decision-making framework combining scene perception and scene reconstruction open control architecture and other technical directions that need to be broken through. It can be predicted that with the convergence and development of USV to system capability, it will form a systematic combat capability of “awareness-decision-control” at different levels of strategy, campaign, and tactics.

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