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A Review of Situational Awareness and Collision Avoidance Strategy for USV in Complex Environments

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Abstract: Unmanned Surface Vehicles (USVs) can detect and avoid obstacles through carrying equipment. However, obstacles pose a serious threat to USVs during autonomous navigation. These obstacles include buoys, ships, animals and other static and dynamic objects. Therefore, when in complex and changeable environment, USVs rely heavily on the accuracy of environmental identification and the rapidity of obstacle avoidance strategies. This paper provides an overview of the researches that have been proposed over the last decade. Different from traditional autonomous obstacles avoidance, which includes situational awareness, path planning, and control system, this study provides an in-depth overview of obstacle avoidance components into two modules: situational awareness and control system. Finally, this paper puts forward a solution that builds a fusion network constructed from multiple perception sensors, whose different outputs give corresponding control commands for the USV, to effectively reduce the delay in the obstacle avoidance process.

1. Introduction

The marine environment, characterized by its unstructured terrain, wind, waves, currents, and fog, as well as static and dynamic obstacles like ships and buoys. Compared to terrestrial environments, it presents higher uncertainty and danger. In the face of complex marine environment and tasks, the use of advanced manufacturing technology and intelligent equipment is the top priority. An Unmanned Surface Vehicle (USV) is a tiny unmanned vessel equipped with capabilities for autonomous planning, navigation, and environmental perception. It offers numerous advantages, including high efficiency, convenience, safety, low cost, and strong adaptability to complex environments. These vessels can carry various sensing equipment to accomplish a wide range of maritime operational tasks. In the civilian field, USVs can be employed for tasks such as marine environmental sampling and monitoring, marine meteorological observation, maritime search and rescue, seabed exploration and maritime patrol investigations. In the military domain, they are primarily utilized for complex missions including maritime escort, intelligence gathering, surveillance and reconnaissance, anti-surface warfare, anti-submarine operations, and mine countermeasures [1].

In recent years, countries worldwide have been actively formulating development policies and conducting academic research centered on "USV situational awareness technology", aiming for efficient and precise perception to enhance the autonomous navigation capabilities. In 2018, the United States released the Department of Navy Strategic Roadmap for Unmanned Systems [2], proposing to vigorously develop unmanned situational awareness technology and pursue the accuracy of data processing. Subsequently, the US Coast Guard unmanned system strategic plan was released in 2023 [3] to emphasize the further development of high-speed and accurate situational awareness technology. As early as 2012, the European Union defined the concept of intelligent ship in the MUNIN project to assess the feasibility of unmanned commercial ships. Subsequently, in the AUTOSHIP project [4] in 2019, the goal was put forward to surpass the current state-of-the-art level in the technology of autonomous ships in situation awareness and obstacle avoidance system, remote and autonomous navigation etc. In China, "intelligent sensing technology" in 2018 was included in the action plan for the development of intelligent ships (2019-2021) [5] of the State Council as one of the technical difficulties that must be overcame in the development of intelligent ships. The document proposes to carry out research on marine sensing technology and multi-source sensing data fusion technology supported by intelligent hardware. Thus, solving the problem of situational awareness technology has become a major and urgent strategic need of the world's great powers.

In addition to situational awareness, obstacle avoidance is also a key technical factor [6] in how to avoid the impact of static obstacles, sea waves and currents, and other dynamic obstacles, and realize autonomous navigation of USV. The maritime traffic safety law [7] points out that maritime traffic accidents are mostly caused by collision, hitting rocks, touching, fire, wind disaster, wave damage and other reasons. According to the 2024 annual overview report on maritime casualties and other accidents issued by the European Maritime Safety Agency (EMSA) [8], 51.7% of accidents occurred in inland waters (port area and others), followed by territorial waters and international waters from 2014 to 2023. Therefore, to adapt to the tasks in different complex environments, and considering the characteristics of USV, such as small volume, small inertia, small blind area, excellent manoeuvrability, strong concealment and so on, USVs, as the active avoidance party, can better ensure their safety in the actual navigation process.

The following sections focus on the two major technical challenges of USV, namely situational awareness and collision avoidance strategy, as mentioned above: discuss the present state of two technologies, and highlight the deficiencies and problems to be solved. In the face of a variety of complex marine environment, especially when its communication is disrupted or remote control, the USV should be able to operate independently without the continuous control or supervision from operator. USV should be able to accurately perceive the environment, achieve rapid collision avoidance planning, and then submit the results of the collision avoidance planning to the Control Subsystem to complete the task independently.

2. Consistence of USV System

A fully-equipped USV, show in Figure 1, consists of three parts: a hull platform system, an autonomous navigation system, and a task load system, with these three systems integrated via universal interfaces. The autonomous navigation system includes five subsystems: Propulsion and Power System, Control subsystem, Interaction subsystem, Communication Subsystem and

Perception Subsystem. The hull platform system and the autonomous navigation system both constitute the most basic general unit of the USV which can operate independently. It is a carrying platform designed to complete different tasks.

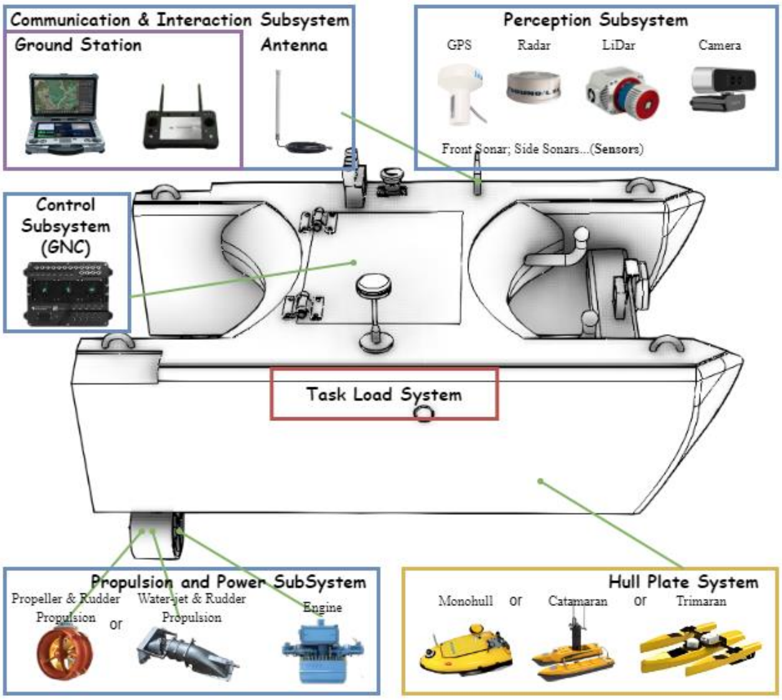

Figure 1: Composition of fully-equipped USV systems.

This paper focus on the Control Subsystem and Perception Subsystem, as shown in Figure 2: including the hardware and software design of the Control Subsystem, which is the "brain" of the USV. Through the onboard equipment, USV realizes the situational awareness (processing and analysing the external space and internal state information), and realizes the functions of autonomous navigation and obstacle avoidance according to the collision avoidance strategy.

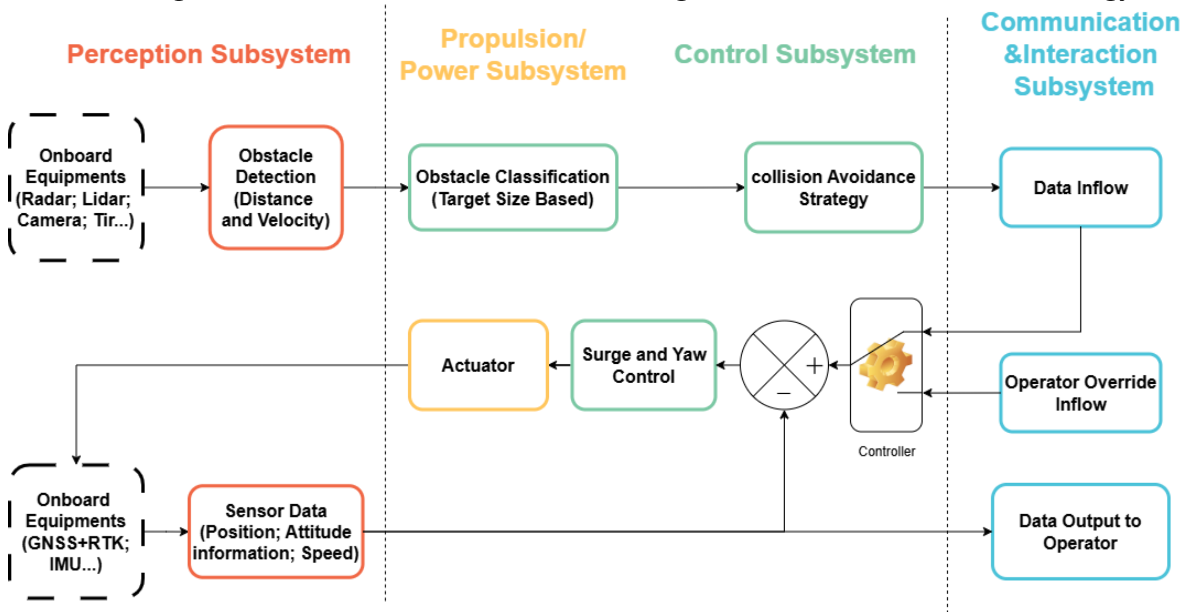

Figure 2: Process of autonomous navigation system.

3. Situational Awareness

Situational awareness technology is the key to the automatic navigation system. By using radar, camera and other sensors to detect and collect the surrounding environment, the technology can obtain a variety of information, such as the relative distance between USV and the static and solid objects, the motion state and motion angle of USV. Therefore, situational awareness can be broadly classified into two main categories: one is the perception of USV's own state; The second is the perception of the external environment.

The perception of USV's own state can be achieved through GPS and IMU. According to the method of information acquisition, external environment perception can be divided into three types: active perception, passive perception, and fusion perception.

3.1. Active Perception

Active perception is a way for sensors to actively send detection signals to the outside and receive return signals, without the need for other intelligent technologies or human intervention.

3.1.1. Marine Radar Perception Technology

Marine radar is used for long-distance detection and tracking of maritime targets, which has a wide detection range and can work all day. In 2009, The ROAZ USV team evaluated the target detection capability of Marine radar under different weather conditions [9], and found that the installation height of antenna affects the detection range of marine radar. At the same time, the marine radar image has two disadvantages: the data noise is relatively high; Insufficient detection capability for small targets. To solve these problems, Jia-yuan Zhang [10] et al. established an embedded collision avoidance system based on marine radar: optimizing the target detection algorithm for marine radar image and collision avoidance algorithm, so that the autonomous navigation of USV has long adaptability and relative stability. Bo-ran Li. designed a set of target detection system [11] based on radar technology, which prioritizes obstacles; Add prediction algorithm; and propose a detection method based on large target contour features, to improve the accuracy of Radar target detection.

3.1.2. Lidar Perception Technology

Lidar uses laser as a carrier wave, which is an important tool for detecting and identifying underwater targets, measuring water depth and studying the optical properties of water. It has the characteristics of high resolution, sensitivity and detection accuracy [12]. In the late 1970s, NASA successfully developed an Airborne Ocean Lidar with scanning and high-speed data recording capabilities, which was used to map the seabed topography in the field. Later, lidar was used for obstacle detection, but the research found that the robustness of lidar was poor. Wang S [13] et. al. proposed a ship and coastline recognition method based on USV equipped LIDAR point cloud data. Based on the three robust target features of relative length, aspect ratio and the scale of point cloud, the target echo data and noise band are analysed and filtered, and the K-Nearest Neighbours (KNN) classification method is used to identify obstacles. Yue Zhao [14] et. al. and others used lidar to collect the point cloud data of USV and navigation process, and built a variable size grid map. Using data mining method, hypothesis tracking model, Kalman filter and other methods to perceive and track obstacle information, and complete stable obstacle avoidance. However, lidar is easily affected by weather factors, and a single sensor cannot work in extreme weather such as snow and rain.

3.1.3. Millimeter Wave Radar Perception Technology

Millimeter wave radar is a radar that works in the millimeter wave (30ghz~300ghz frequency domain, 1mm~10mm wavelength) band. It has the characteristics of wide detection range, strong penetration ability and small volume. However, due to the complex environment and the different scattering intensity of obstacles, it will be interfered by noise, which is easy to cause false alarm. To solve this problem, Cao Lin[15] et al. proposed a method to identify marine obstacles and millimeter wave radar sensor information without joint calibration, which is used to detect and identify marine obstacle targets. This method extracts the position and speed of the target as the feature vector, and designs the matching evaluation function to find the best match from the data information of the two sensors, which improves the efficiency of marine obstacle target recognition. Aiming at the target missing phenomenon of millimeter wave radar, Zhai G [16] et al. proposed a target tracking algorithm based on an adaptive Kalman filter, and verified the accuracy of the target information estimated by the algorithm. Although some problems have been solved, millimeter-wave radar still has the problem of small detection angle and range.

3.2. Passive Perception

The vision camera sensor transmits the image projected to the sensor through the lens to the device that can be stored and analyzed. It has the features of light weight, low power consumption and rich information. In recent years, the research of image processing technology has made great progress. Water surface target detection based on image processing technology can generally be divided into two categories: traditional object detection and Deep Learning-based Object Detection.

3.2.1. Traditional Object Detection

The traditional target detection algorithm can be divided into two methods: sliding window-based target detection method and texture-based target detection algorithm. In essence, both of them select candidate regions first, then extract features according to Scale-Invariant Feature Transform (SIFT) [17], Histogram of Oriented Gradient (HOG) [18] et al. methods, and finally use Support Vector Machine (SVM) [19], Random Forest and other classifiers to classify, so as to transform target detection problem into classification problem, then realize target detection. In order to solve the problem of complex water environment changing constantly, Yi-Hui Zhang [20] et al. took three steps: target image pre-processing, target segmentation and feature extraction, and LVQ neural network training with image features. Finally, the target recognition rate reached 94.4%. But there are problems of high delay and poor accuracy.

Traditional target detection algorithms can meet the needs of simple applications to a certain extent, but with the continuous improvement of users' requirements for real-time in practical applications, high-precision and fast deep learning target detection has gradually become the mainstream technology.

3.2.2. Deep Learning-based Object Detection

Deep learning technology can be classified according to two aspects. At first, according to the model architecture, such as Convolutional Neural Networks (CNN), Recurrent Neural Network (RNN), Convolutional Recurrent Neural Network (CRNN) [21][22]; The second is the training method by model, including supervised learning, unsupervised learning, semi supervised learning and so on. The Deep Learning-based Object Detection mainly uses CNN for feature extraction. According to the detection process, it can be divided into Two-stage and One-stage. The former one is based on the method of generating candidate regions. Such as Kai-ming He proposed SPP-Net

[23] and Fast R-CNN[24] target detection networks, which have good detection effect but slow efficiency. The One-stage target detection algorithm only needs a single detection to obtain the final detection result, which not only ensures the accuracy, but also improves the detection efficiency. The most representative two are Yolo (Yolo only look once) and SSD (Single Shot MultiBox Detector), Regression-based Method [25][26].

Through the Deep Learning-based Object Detection algorithm, the water surface target detection is fast, and it can ensure high accuracy. For the small sample marine target detection task, Bo Wang[27] et al. designed a lightweight marine target detection network ISDet to improve the efficiency and average accuracy of feature fusion. To address the challenges in inland river's water surface target detection under complex environment, such as big ambient noise, intricate distribution of water surface targets, tiny and indistinct features, Siyu Ren [28] et al. proposed a water surface target detection algorithm, namely UltraWS, which integrates multi-scale features and attention mechanism and enhances Class Activation Mapping (CAM). For complex marine environment, Cheng Yu [29] et al. introduced MCA mechanism to establish long-distance dependence between pixels based on the lightweight YOLOv8 model; Simplified SimSPPF to the backbone to improve the prediction accuracy; optimized the convolution layer to reduce the model parameters. These methods effectively balance the detection accuracy and computational efficiency compared with the original model.

3.3. Fusion Perception

The above discussion shows that sensors are an important means for USVs to perceive the real-time environment and ensure safe navigation. Generally, perception technologies include marine radar, Lidar, millimeter-wave radar, visual camera and others. Table 1 shows the Advantages and disadvantages of various perception technologies.

Table 1: Situation of various perception technologies.

Name of perception technology	Advantages	Disadvantages
Marine radar	Wide detection range, all-weather capability	Vulnerable to metal obstacles, weak anti-interference performance
Lidar (laser radar)	Compared with marine radar, it is more suitable for close range object detection	easily affected by weather factors
millimeter-wave radar	High resolution and accuracy, strong penetrability, small volume and all-weather capability	small detection angle and range
visual camera	Light weight, low power consumption and rich information	easily affected by weather factors, feature extraction of visible image is difficult

Due to the shortcomings of various sensing technologies, it is difficult to achieve the desired sensing effect only by relying on a single sensor. Therefore, many researchers at home and abroad enhance the reliability and accuracy of water surface object detection by integrating sensors with different functions to obtain information sources.

In 2019, Chinese and foreign scholars proposed the method of integrating millimeter-wave radar and lidar [30][31], and applied the fusion data in many aspects: water surface object detection; Judging the movement situation of close-range targets; improving the ability of independent berthing. Compared with the single sensor, the error accuracy of the target spatial position information, obtained by the fusion system is smaller. At the same time, they pointed out that the future and vision sensor fusion is a higher-level research direction. In order to enable lidar to obtain more accurate data information in the degraded scene, Wisth D [32] et al. proposed a data fusion method of camera, lidar and inertial measurement unit (IMU), which improved the estimation accuracy of multi-sensor system in degraded scenes. In an effort to dynamically optimize the energy consumption of USV, Liyong Ma [33] et al. proposed a visual target recognition method by combining YOLOv5 and DeepSORT, used target number provided by radar to dynamically adjusting the threshold of visual target recognition, so as to improve the accuracy of target detection result. To address the problem of missed detection by solely visual target detection, Yongguo Li [34] et al. optimized YOLOv7 algorithm, then fused visual and LiDAR point-cloud information.

The methods proposed by the above scholars are similar in nature. Most of them are based on how to fuse multiple sensors to improve the positioning and recognition accuracy of water surface targets. Generally speaking, fusion perception is the current trend of situational awareness Technology.

4. Collison Avoidance Strategy

The collision avoidance strategy is to plan a collision free path that meets the dynamic constraints of USV in real time based on the environmental perception information. The research on obstacle avoidance technology of USV in foreign countries started earlier. Benjamin M R[35] et al. proposed the interval planning multi-objective optimization algorithm based on the behavior control framework, used the International Convention for the prevention of collisions at sea rules to regulate the obstacle avoidance behavior of USV on the surface. Mousazadeh H[36] et al. proposed a fusion obstacle avoidance algorithm based on EKF, search ball and potential field concepts. Through the self-designed catamaran Morvarid to evaluate obstacles, the fusion algorithm has strong robustness and accuracy. Domestic research started relatively late. Jinlin Xiang[37] et al. proposed an improved two-way sampling based (RRT) local path planning algorithm against the background of high-speed USVs, which accelerated the convergence of the algorithm and had better obstacle avoidance effect. Aiming at the problem that it is difficult to avoid obstacles in real time due to the lack of global obstacle location in the location environment, Yuhang Ji [38] et al. proposed a dynamic obstacle avoidance method combining deep neural network and improved artificial potential field method. Dengyao Jiang[39] et al. proposed a Random Walk Policy Twin Delayed Deep Deterministic Policy Gradient (RWTD3) algorithm. After training, the USV can realize collision free navigation from any starting point to a given destination in the environment of wave, current interference and complex static obstacles.

Table 2: Situation of various Collison avoidance strategy.

Type of Collison avoidance strategy	Advantages	Disadvantages
Based on optimized local path planning algorithm	The algorithm logic is clear and easy to deploy in embedded system	easy to fall into local optimum in complex environment, the prediction accuracy decreases in high-speed scenes, Performance is greatly affected by evaluation function parameters
Based on deep reinforcement learning	Strong adaptability: through training, USV can adapt complex environment	Require a large amount of data to train the model, and the real-time performance is affected by the training cycle
Based on sensor and algorithm fusion	Reliable obstacle detection, Millisecond response can be realized	Hardware dependent, high cost

To sum up, the research on collision avoidance strategies of USV at home and abroad can be divided into three types, as shown in Table 2: first, obstacle avoidance based on optimized local path planning algorithm, second, obstacle avoidance based on deep reinforcement learning, and third, obstacle avoidance based on sensor and algorithm fusion. The original local obstacle avoidance strategies, such as artificial potential field method, ant colony algorithm, bacterial foraging optimization, artificial neural network algorithm, have good effects in known, fixed and small-scale environments. However, when USVs face a complex and changeable marine environment, the original obstacle avoidance strategy is difficult to quickly respond to environmental changes. Therefore, in the complex marine environment, the research on the fusion has become an important path for USVs' real-time sensing and autonomous obstacle avoidance.

5. Conclusions

Starting with the analysis of the composition of full-equipped USV system, this article discusses two key technologies of autonomous navigation system: situational awareness and obstacle avoidance strategy. Then, this review summarizes the achievements and shortcomings of these two core technology fields in recent years, categorizes and summarizes the research from domestic and foreign scholars, and analyzes their characteristics. Due to the complexity and unknowns of the USV working environment, it is necessary to continuously improve and perfect existing technologies to enable USVs to accurately, timely obtain environmental information and complete autonomous navigation. The following text presents prospects based on the current research status.

In terms of object detection, the information obtained by using only a single type of sensor is far from sufficient to support USVs for environmental object detection. In the future, a complementary multi-sensor information fusion network should be established to improve the accuracy and speed of target detection.

In terms of obstacle avoidance strategy selection, although local path planning and machine learning algorithms have been greatly optimized in the past decade, real-time information fusion with sensors is a necessary path when facing unknown and complex environments. Meanwhile, the application of collision avoidance strategies for USVs is mostly still in the theoretical or simulation stage. In the future, the characteristics of water conditions in the mission area should be taken into account, which can be closer to the real mission state and improve the practicality of obstacle avoidance strategies in the USV field.

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