

The Wind Power Watch, "Guarding" for Safety - Data-Driven Intelligent Deterrence System for Monitoring Ships in Offshore Wind Farms

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Abstract

This study successfully developed a ship monitoring and repulsion system for offshore wind farms aimed at ensuring the safety and stable operation of the wind farms. The system is capable of real-time monitoring of ship activities and environmental conditions, quickly identifying and eliminating potential safety risks. The research content includes various aspects such as ship detection, path tracking, repulsion decision-making, and data processing. The system integrates multi-sensor data, Geographic Information Systems (GIS), Automatic Identification Systems (AIS) for ships, artificial intelligence algorithms, and advanced communication technologies, constructing an efficient and intelligent monitoring and repulsion framework. Field test results indicate that the system exhibits stable performance and efficient monitoring capabilities under harsh weather conditions, while the intelligent voice repulsion function has shown significant effects.

Keywords

Offshore Wind Farms; Ship Monitoring; Repulsion System; Geographic Information Systems (GIS); Automatic Identification Systems (AIS); Intelligent Voice Repulsion.

1. Project Background and Significance

1.1. Research Background

The "13th Five-Year" plan of the National Energy Administration emphasizes the importance of offshore wind farm construction to promote the development of clean energy and the construction of a modern energy system. With the progress of the global wind power industry, research on offshore wind turbine inspection has received more attention [1]. In recent years, wind power generation is one of the effective ways to achieve the goals of "carbon peak and carbon neutrality" [2].

Offshore wind farms include wind turbines, booster stations, and control centers, which achieve power transmission and distribution through submarine cables. The booster station, as an offshore substation, is connected to wind turbines via 35KV submarine cables and to the onshore control center via 220KV submarine cables. The electricity generated by the wind turbines is first transmitted to the booster station and then distributed by the control center through 220KV submarine cables [3]. Submarine cables face safety risks from the marine environment, especially damage that may be caused by ship anchoring. This paper introduces a ship monitoring system for offshore wind farms, aimed at reducing the damage to submarine cables caused by ships.

1.2. Current Research Status at Home and Abroad

1.2.1. Domestic Research Status:

Offshore wind power generation has received continuous attention and rapid development in our country due to its great potential to promote the energy transition process [4].

Although domestic research on AIS systems started late, it has developed rapidly since 2000. Currently, AIS systems have covered major shipping lanes and adopted a four-level management architecture. By the end of 2018, China had established 1 national AIS data center, 1 backup center, 3 regional data centers, 21 regional data centers, and 182 AIS base stations, achieving continuous coverage within 25 to 30 nautical miles along the coast, covering an area of about 600,000 square kilometers [5]. Chinese AIS system research started with single-machine monitoring and gradually evolved to a C/S architecture, but stability issues were faced. After adopting dual-active hot backup technology, system stability was enhanced, but the expulsion module remained singular. Subsequently, researchers developed a sea cable protection expulsion system, optimized the monitoring interface and tracking algorithm, improved the accuracy and intelligence level of monitoring, and effectively reduced the damage to power sea cables by ships [6]. When the anchor weight of a ship is lower than the sea cable's load-bearing capacity, anchoring is allowed, but the possible sea cable deformation and current abnormalities were not considered. The system mainly provides alarm functions.

1.2.2. Foreign Research Status:

Offshore wind farm vessel monitoring and expulsion systems are unique technological systems, and international research in this area is also being actively promoted.

Europe has achieved significant results in the construction of offshore wind farms and vessel monitoring and expulsion systems, which have been applied in multiple projects. The European Marine Energy Management Platform (EMD) uses the VTS system to closely monitor maritime traffic. The Marine Data Platform initiative was launched in Oslo, Norway, in October 2019, in collaboration with C4IR Norway, and became part of the Global C4IR Network initiated by the World Economic Forum [7].

North America is an active area for the construction of offshore wind farms, and the United States has made progress in vessel monitoring and expulsion systems. The "Dolphin System" developed by MIT uses acoustic technology to provide high-resolution images. Synthetic aperture sonar (SAS) and interferometric synthetic aperture sonar (In SAS) technologies have attracted attention in the underwater engineering field due to their high resolution and rapid mapping rates. Significant progress has also been made in navigation, autonomous underwater vehicles (AUV), sonar technology, and electronics in recent years [8]. Detecting the location and speed of non-AIS vessels. The United States is researching and piloting offshore wind power monitoring systems.

Asian countries have researched and applied similar systems. Japan and Korea have developed offshore wind power and improved maritime facilities. Foreign research has achieved results and formed advanced technologies. The development of the offshore wind power industry will promote these technologies.

2. Research Content and Technology

2.1. Research Content

The offshore wind farm monitoring system utilizes sensors to monitor ships in real-time, analyzing their motion characteristics to identify threats and execute repelling operations, ensuring a safe distance. The system features functions such as ship detection, path prediction, safety assessment, and collision risk determination, and is adaptable to various marine environments.

This paper discusses the development of an offshore wind farm ship monitoring system that possesses high availability and comprehensive functionality, providing real-time monitoring of ship activities in the surrounding sea areas, identifying and repelling dangerous ships that may threaten the submarine cables, and ensuring the safety of the cables. The system employs electronic fencing and acoustic-optic warning technologies, offering traffic monitoring, early warning, and maintenance services, aiming to ensure the safety of wind farm construction and operation, and to maintain navigational safety [9]. The solution utilizes the AIS system to collect ship data, with classification and storage performed on the server side. Users achieve data visualization and electronic fencing construction through the client and GIS system, enabling real-time monitoring of ships. The system can identify dangerous ships and issue alerts, notifying monitoring personnel to handle risks, and sending voice warnings and repelling information. The system integrates sensing, communication, and machine learning technologies to reduce the risk of collisions between ships and wind power equipment, ensuring the safety of the wind farm. The system supports multiple clients, featuring functions such as alerts, data visualization, automatic announcements, electronic fencing, and risk assessment. The system architecture is shown in Figure 1.

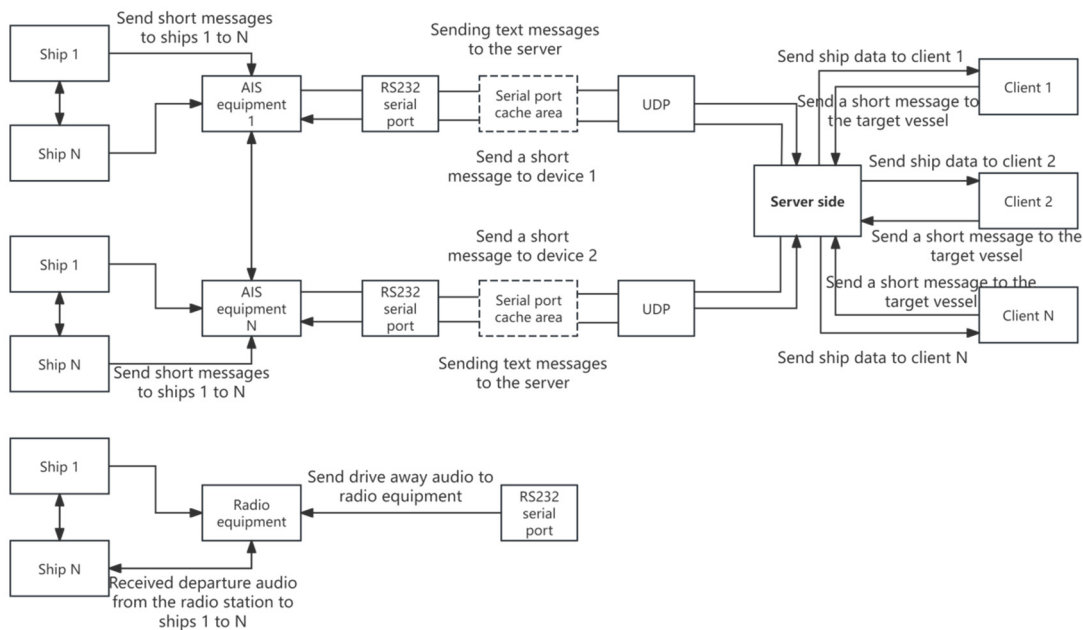


Figure 1. System Architecture Design Diagram

2.2. System Architecture and Components

Offshore wind farms are developing rapidly, but there are issues with vessel safety. We have developed a data-based monitoring system that integrates AIS, GIS, sensors, AI algorithms, and communication technologies to monitor and manage vessels efficiently and intelligently. The system tracks vessels in real-time through AIS, visualizes information through GIS, assisting monitoring personnel in identifying risks.

The sensor network deploys multiple nodes to monitor environmental parameters such as wind speed, wind direction, and ocean currents. Wireless sensor networks (WSNs) are emerging military and civilian technologies suitable for remote and unattended environments, possessing hierarchy and chaos [10]. The artificial intelligence system analyzes vessel and environmental data, predicts risks, and formulates strategies to drive away, guiding vessels to avoid dangerous areas in real-time, ensuring the safety of the wind farm. The communication system ensures real-time communication between vessels and the monitoring center, facilitating the sending of warnings or guidance information. This data-driven monitoring

system enhances the safety, efficiency, and competitiveness of wind farms, while reducing collision risks. The system integrates monitoring, control, and driving-away functions, providing comprehensive monitoring of maritime traffic, adjusting wind turbine status, and ensuring the safety of the wind farm.

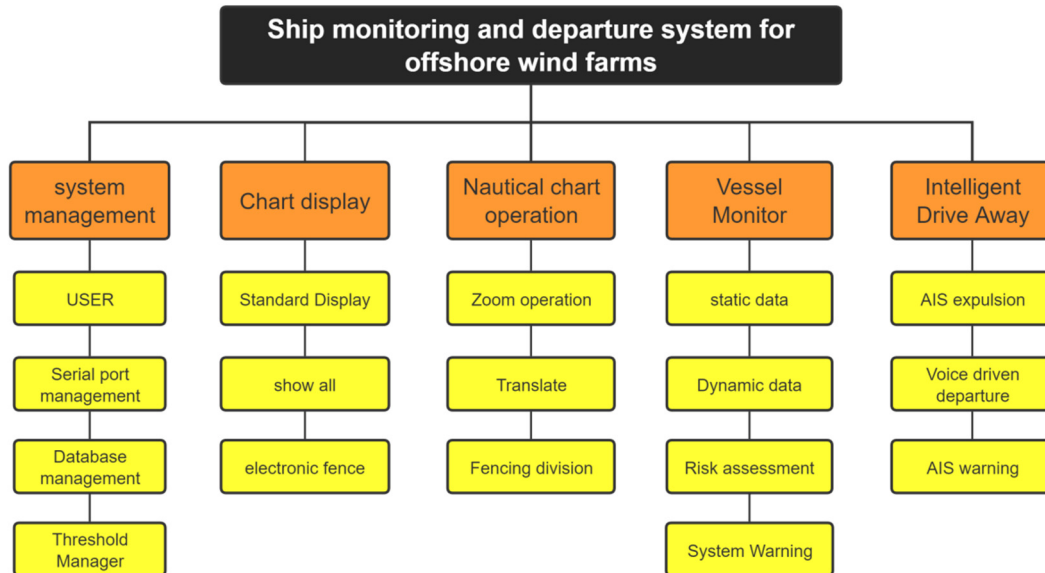


Figure 2. Overall Functional Structure Diagram of the System

2.3. Electronic Fence Architecture

2.3.1. Creating an Electronic Fence

The system creates electronic fences using GIS layer technology to track the location of ships in real-time. To prevent the concentration of geographic information from affecting system performance, multi-layer overlay technology is applied. The system layers are divided into three categories: static data, non-fixed position dynamic data, and fixed position dynamic data. Among these, the fixed position dynamic data layer is processed by the visualization module, and the details will not be elaborated upon here.

(1) The static data layer is the foundation of the geographic information for offshore wind farms, displaying buildings and wind turbines with points and images, and using line elements to represent submarine cables and electronic fence areas. Users can modify the coordinates of submarine cables and electronic fences.

(2) The non-fixed position dynamic data layer displays ship AIS information in a similar way to the static layer, but it needs to be updated regularly to reflect the real-time position of ships and to remove old location data.

2.3.2. Electronic Fence Area Ship Discrimination Algorithm:

If the system needs to implement the repulsion of ships in the waters near the wind farm, it first needs to determine whether the ship is located in the area where submarine cables are laid. Combining electronic fence technology, the specific discrimination steps are as follows:

(1) Abstract the closed area delineated by the electronic fence as an irregular polygon with n vertices, setting the coordinates of each vertex as (X_i, Y_i) ($i=0\dots n-1$).

(2) Set the coordinates of the point where the ship is located as (X, Y) , and draw a line parallel to the x-axis to the right through each closed area.

(3) Record the number of intersection points where the line intersects with the irregular polygon, denoted as C ($C>0$).

(4) If (X_p, Y_q) is on the edge or vertex of the polygon, then determine whether the ship is located in the area of the electronic fence where submarine cables are laid, and whether the ship needs to be monitored in real-time.

As shown in Figure 3, the first ray intersects the polygon at two points, indicating that the ship is outside the submarine cable laying area; the second ray intersects at four points, also indicating that the ship is outside the submarine cable area; the third ray intersects at three points, indicating that the ship is within the submarine cable laying area and needs real-time monitoring.

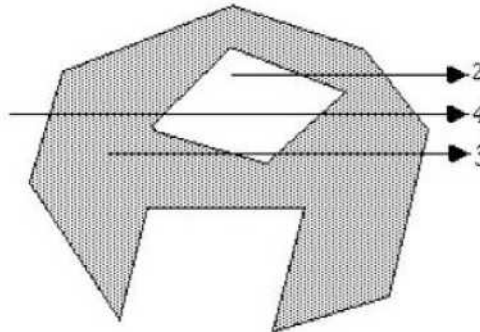


Figure 3. Simulated ship location diagram

2.4. Monitoring Technology

Anchor Damage Risk Discrimination Algorithm Design:

An algorithm has been developed to identify the risk of ship anchoring, which is based on three main factors: speed, heading, and draft depth. It performs a weighted analysis of these factors through a risk warning model. Additionally, the system continuously monitors vibration signals near submarine cables to assess whether they are within the normal range. If the detected vibration signal parameters are normal, it is determined to be an anchor damage signal, and a warning is issued at the corresponding location [11].

This system mainly prevents two types of anchoring: backward anchoring and deep-water anchoring. Backward anchoring is a common method used by ships, requiring Slow down or reverse to drop anchor. For example, when dropping the port anchor, the ship must deviate to the left by a certain angle, reverse, and then the bow will swing right to the predetermined anchorage position, after which the anchor is dropped at a speed of 0.5 knots in reverse. Deep-water anchoring involves letting out a certain length of anchor chain before reaching the anchorage point, arriving at the predetermined location at a speed of 0.5 knots or less, and immediately dropping the anchor. After anchoring, the ship's draft will increase.

The factors that mainly affect the safety of submarine cables in wind farms due to ship anchoring are speed, heading, and draft volume. When the speed is below the threshold, the ship is classified into a specific sequence; above the threshold, it is considered the end of anchoring and may begin sailing [12]. When the ship's speed is below 0.5 knots or in reverse, a change in heading is considered high risk. The risk warning model is applicable to the area of submarine cable laying, involving speed V , heading C , total draft S , and standard draft M .

Table 1. Risk Early Warning Model

Risk factor 1	Risk factor 1	Risk factor 1	Warning content
Section $V < 0.5$	C is skewed to the left or to the right.	$S > M$	There is a risk of the ship anchoring.
$0.5 \text{ section} < V < 3$	C is not deflected	$S < M$	Abnormal ship speed
$0.5 \text{ section} < V < 3$	C is skewed to the left or to the right.	$S < M$	There is a risk of the ship anchoring.
Section $V < 0.5$	C is not deflected	$S < M$	Abnormal ship speed

The workflow involves collecting vessel information and using an electronic fence algorithm to determine if the vessel is within the monitoring area. If the vessel is in the monitoring zone, the system will alert for cable laying; if it is in the laying area, it will prompt the vessel to avoid it. The system also analyzes data such as vessel speed, heading, and draft to assess risks and issues warnings or orders to disperse based on the assessment results.

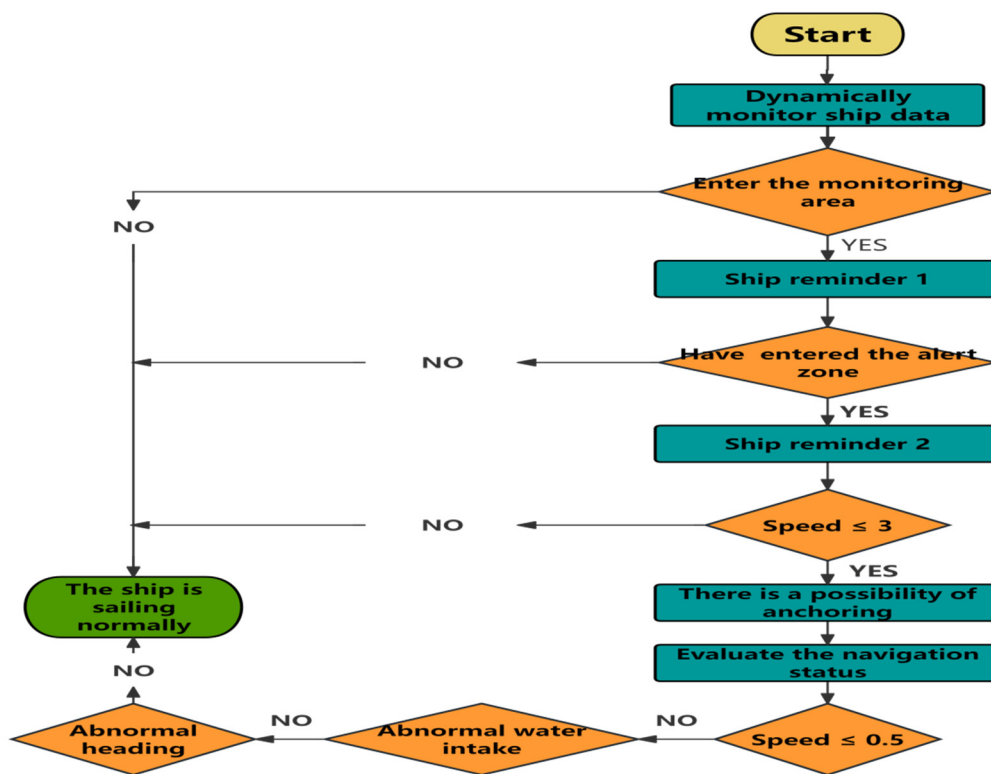


Figure 4. Anchoring Risk Discrimination Algorithm Flowchart

2.5. Audio Broadcast Repulsion Module

This module, by modifying VHF radios and analyzing Wav audio files, designs a voice alarm system used to effectively repel dangerous vessels and enhance the repulsion efficiency of offshore wind farm workers. The audio broadcast repulsion module utilizes VHF radios to send synthesized audio to the maritime public safety frequency band, actively repelling dangerous vessels in real-time. The client extracts high-risk vessel data from the server, and the system automatically generates repulsion voice messages based on the vessel's MMSI number and name. The multifunctional enclosure converts audio into radio input, which is then played through the VHF antenna to nearby vessels in the area, completing the repulsion task. VHF communication is widely used in the maritime field, including satellite-based communication and vessel tracking. The International Telecommunication Union has proposed the concept of a composite VHF Data Exchange System (VDES), aiming to integrate the functions of existing systems [13].

AIS, or the Automatic Identification System, is a shipborne broadcast response system. It allows ships to broadcast their identity, location, course, speed, and other information to surrounding vessels and shore authorities via VHF public radio channels [14]. The system uses an IC-M304 VHF radio for communication, operating within the VHF band. Unlike AIS equipment, it can efficiently send instructions to target vessels through voice or audio communication. Using the maritime safety public channel 16, all vessels can receive the same message, facilitating the simultaneous warning of dangerous vessels and other ships. The connection of the audio broadcast repulsion module is shown in Figure 5.

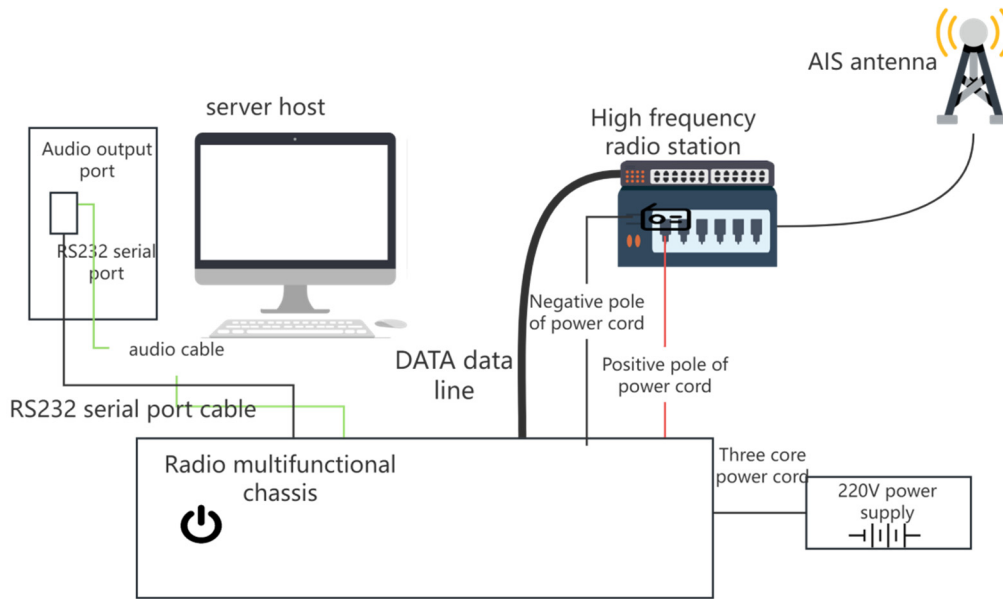


Figure 5. Audio Voice Eviction Device Connection Diagram

The software executes the eviction command in three main steps: first, it stores the vessel data into a secure queue; next, the audio eviction module reads this data via the UDP protocol; finally, the module generates and plays the eviction audio, sending it through the radio. The server's main thread starts a dedicated audio processing thread, which has its own queue and UDP channel to ensure that communication with AIS is not disrupted. The audio thread retrieves data from the queue, synthesizes eviction audio for specific MMSI numbers, and sends it through the radio. The multi-threaded implementation of the audio eviction function is shown in Figure 6.

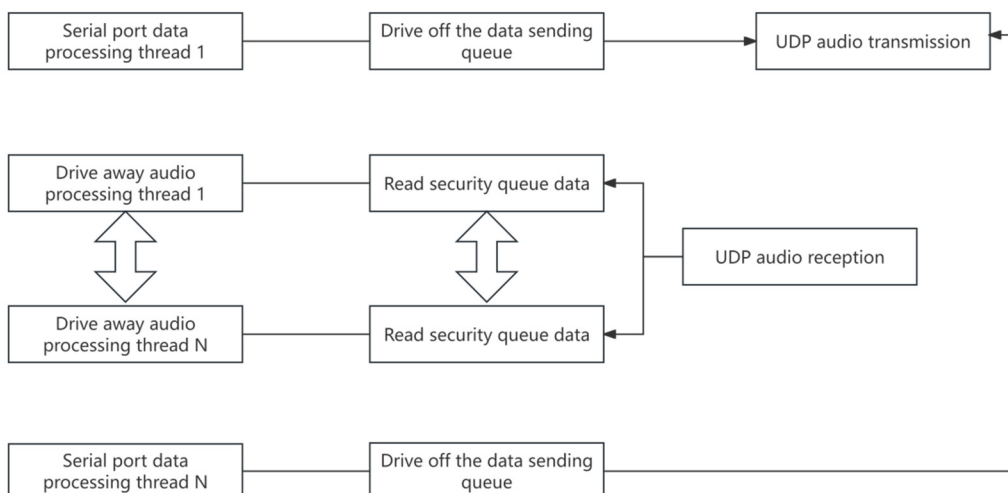


Figure 6. Multithreaded implementation of the audio eviction function

The implementation process of the audio synthesis module includes:

- (1) The server receives the MMSI number of the vessel sent by the upper computer and stores it in a secure queue. The audio callout expulsion module reads these MMSI numbers, which must meet consistency and integrity to ensure the unification of vessel information. The MMSI code consists of 9 digits and is used for the unique identification of vessels at sea, which is crucial for the identification, tracking, and management of vessels [15].
- (2) The system determines whether the format of the vessel MMSI number is standard (usually a nine-digit number).
- (3) After passing the verification, the audio synthesis module uses the cTxt method and ofstream operation to create a text file containing the vessel MMSI number, which facilitates tracking the responsibility of dangerous vessels.
- (4) The system calls the OpenWaveFile method through the MMSI number to load the corresponding wav audio file from the specified path. This method converts the audio file into a byte stream and checks whether it conforms to the standard wav format, including the identification, length, sampling frequency, and speed of the block area. The verified byte stream is stored in different arrays by region.
- (5) Before synthesizing the audio, the CutWave method extracts the Data byte stream array of the audio and merges them two by two, ultimately synthesizing a Data byte stream array.
- (6) Finally, the SaveWaveFile(const char name, Byte wav1) method matches the corresponding RIFF WAVE block, Format block, and Fact block for the synthesized Data array, merges the arrays according to the wav format, and stores this expulsion audio locally for the main program to call.

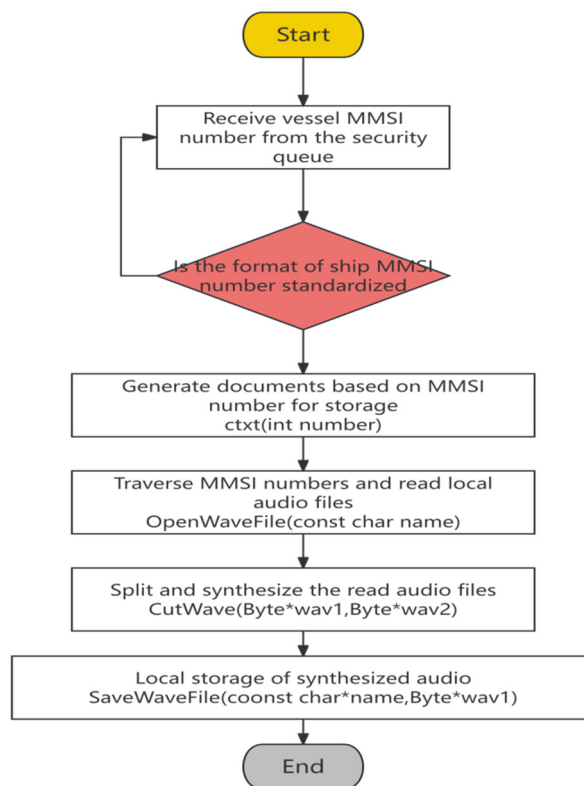


Figure 7. Audio Synthesis Module Program Flowchart

3. Project Research

3.1. Key Technologies of the Project

The offshore wind farm monitoring system tracks the sea area in real-time, collecting vessel information through AIS and GIS technologies. If a dangerous vessel is detected approaching, the system will automatically send out warning text messages and notify the relevant vessels, while also using public safety channels to issue audio warnings to drive away the vessel. This system ensures the safety of the wind farm, continuously monitors the conditions of vessels and the environment, and effectively prevents risks.

The development of a vessel monitoring system includes data acquisition and forwarding, servers, and clients. AIS data collected by VHF antennas is transmitted between these components, where the data acquisition and forwarding process handles the encoding and packaging of AIS information; the server software is responsible for storing and retrieving data, performing computational analysis, and finally feeding the results back to the user terminal [16]. The client retrieves vessel information from the database for corresponding processing.

The system analyzes the IEC 61162 and ITU-R M.1371 protocols to implement the encoding and decoding of AIS messages. It uses multi-threading technology to improve task management and response speed, and protects data transmission through secure queues, preventing thread locks from affecting efficiency.

Furthermore, the system utilizes the PostGIS geographic information database and MapWinGIS spatial to implement the system background map data, where MapWinGIS is a virtual simulation system development framework with storage and processing capabilities [17]. The offshore wind farm map and electronic nautical charts assist in monitoring vessels. By analyzing the anchoring characteristics of vessels, a risk early warning model is established, and an anchorage risk discrimination algorithm based on factors such as speed, draft depth, and heading is designed to achieve efficient monitoring and accurate expulsion of vessels.

The development of an audio hailing expulsion system includes hardware upgrades to directly control VHF radio. Using C++ and Wav format, a structure for audio file synthesis is created. System testing has shown that it can respond quickly and accurately to anomalies and automatically activate related equipment [18]. The technology roadmap is shown in Figure 8, with the following detailed introduction of the specific technology roadmap.

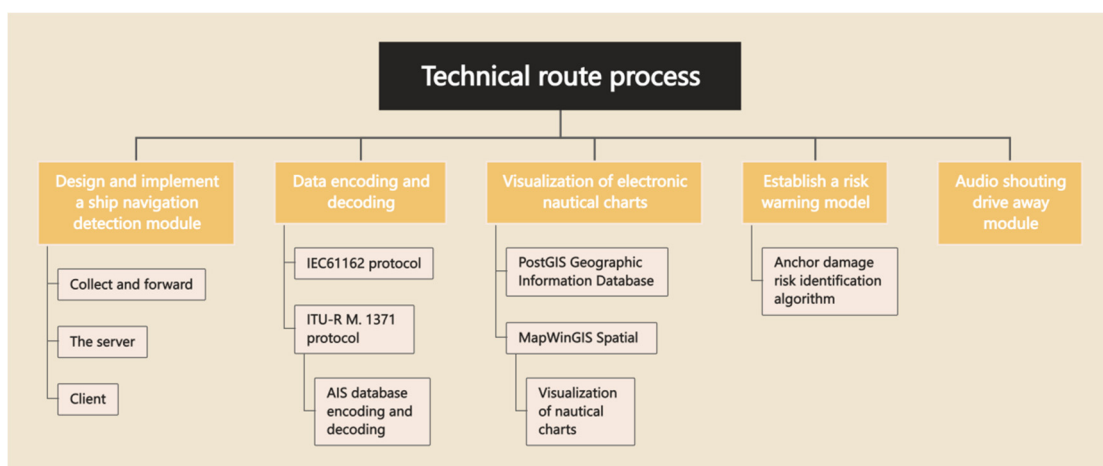


Figure 8. Technology Roadmap Flowchart

4. Summary and Outlook

Offshore wind power projects face high safety risks and require strict supervision. The document from five ministries has clarified the specific responsibilities of maritime authorities in safety prevention and control. Maritime authorities should recognize the key role of offshore wind power in improving China's energy structure and promoting the development of the marine economy [19]. In the future, we will continue to focus on the clean energy market and technological innovation, strengthen technology research and development, and enhance competitiveness. In terms of market promotion, we will actively expand domestic and international markets, strengthen cooperation, and promote the application of offshore wind power technology. At the same time, we plan to participate in international cooperation, share experiences, and promote the globalization of the offshore wind power industry.

The Chinese government has set the goal of reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060, aiming to transition from relative emission reduction to absolute emission reduction and ultimately to zero emissions. This demonstrates its ambitious "China Solution" and road map [20]. We believe that this project will drive the development of the marine engineering field, bringing opportunities and challenges. We will continue to pay attention to policies, technology, and the market, optimize project implementation, and support China's offshore wind power industry. At the same time, we are willing to explore the future of offshore wind power with an open and cooperative attitude.

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