Intelligent anti-collision warning method of fairway buoy based on passive underwater acoustic positioning

Shuai Chen¹, Haowen Xiang¹, Shuangyin Gao²

¹ School of Shipping, Wuhan University of Technology, Wuhan 430063, China
² School of Energy and Power Engineering, Wuhan University of Technology, Wuhan 430063, China

Corresponding author’s e-mail: 1469524811@qq.com

Abstract. In recent years, there have been frequent safety accidents of ships striking fairway buoy, which has aroused great concern. This paper firstly analyzes the causes of the collision of ships with navigation marks, and then proposes an intelligent anti-collision warning method of navigation marks based on passive underwater acoustic positioning. This paper has designed a kind of intelligent anti-collision navigation marks. The underwater acoustic transducer is installed under the navigation marks to complete the acquisition of distance information between the ship and the navigation marks. When the dangerous ship enters the dangerous water area set in this article, through the early warning matrix lights mounted on the navigation marks and the AIS information center, targeted warnings are given to dangerous areas where dangerous ships are located. The supply-energy analysis results show that this intelligent anti-collision warning navigation mark generates more electricity per day than its power consumption, and at the same time, the rich electricity can be filled with lithium iron phosphate batteries, which guarantees the daily work of this navigation marks and provides stable power support for all parts of the navigation mark. This intelligent anti-collision early warning method can give full warning to dangerous ships, avoid the collision of ships with navigation marks, and ensure the safety of navigation at sea.

1. Introduction
In recent years, with the in-depth implementation of the “Belt and Road” strategy, the country has increased the construction of ports and waterways, the throughput of ports has expanded, the volume of shipping has increased, and the marine economy has developed rapidly. It should also be observed that the vigorous development of the shipping industry puts forward higher requirements for the marking function of the navigation mark. It is estimated that by the end of 2020, there will be about 20,144 navigation marks set up along the coast of China[1]. Only over 100 orders were suspected to be hit by the Guangzhou navigation mark in 2018[2], which caused serious damage to the navigation marks and hulls, not only does it need to spend a lot of manpower and material resources to repair, and even the navigation channel cannot be correctly marked due to damage to the navigation mark, which brings great hidden danger to the safety of navigation at sea. Therefore, from a long-term perspective, for the objective collision between the ship and the navigation mark, sufficient attention should be paid to the collision factor investigation, and a set of navigation mark anti-collision warning methods should be designed according to the cause of the collision to reduce the incidence of collision accidents.

In the relevant literature, most of the research objects are centralized management of ship marks based on CCTV monitoring system[3,4] or underwater sound detection technology[5], and the collision...
problem between ships and navigation marks has not been fundamentally solved. In addition, the research on preventing collisions between ships and navigation marks is rarely mentioned in the literature.

In this paper, an intelligent collision warning method based on passive underwater acoustic positioning for navigation marks is a new way to solve the collision between navigation marks and ships. It is of great practical significance for reducing the collision of navigation marks, guaranteeing the safety of shipping and promoting the development of shipping.

2. Classification of ship collision navigation mark factors

2.1 Environmental factor
Environmental factors are mainly reflected in the waterway environment and the natural environment.

(1) The ship's scale is not suitable for the channel, the construction area makes the channel narrow, and the channel environment causes the ship's handling space to narrow. The location of the navigation mark is improper, and it is located in a section with complicated bends or turbulent water flow. The position of the ship is greatly affected by the water flow and is not easy to control. It has a great test on the manipulation skills of the ship pilot.

(2) Unfavourable weather such as foggy weather, swells, strong winds, etc., will reduce the visibility of the ship's pilots and cannot maintain a normal lookout to the navigation mark. Therefore, once the ship sails adventurously, the probability of collision with the navigation mark will be greatly increased. In addition, due to the impact of the nighttime lighting project in the navigable city, the background light pollution of the city and the bridge is serious, making the navigation marks that rely on the point light source to be submerged in the bright background lights, which are difficult to be recognized by the ship's pilot, and it is easy to cause the ship to yaw or collide with the navigation marks.

2.2 Ship factor
The ship factor is mainly reflected in the seaworthiness and ship performance.

(1) The seaworthiness of the ship means that all aspects of the ship meet the general safety requirements during navigation and operations, and can withstand the risks that normally occur during the voyage or can be reasonably foreseen.

(2) The performance of the ship is an important factor that affects the safety of navigation. Factors such as the steering gear of the ship, the failure of the main power supply, the failure of the navigation system, the suitability of the type and scale of the ship relative to the channel, etc. all directly or indirectly cause the ship to collide with the navigation aid occur.

2.3 Human Factors
According to statistics, 90% of water accidents are caused by human factors[6]. Human factors mainly include inexperience of ship pilots, unlicensed driving, and speculative thinking. The specific details are shown in Table 1.

| Factor classification | Detailed description |
|-----------------------|----------------------|
| Ideological speculation | Compared with collisions with bridges and ships, collisions with navigation mark have much smaller economic losses, social attention, and legal liabilities. In addition, there is still a lot of room for improvement in obtaining evidence after a navigation mark collision, which provides an opportunity for the offending ship. |
| Insufficient experience | The driver's cultural quality is low; unfamiliar with navigation regulations, the driving skills need to be improved; the performance of the piloted ship is not familiar enough, and the operation is not skilled enough; when a danger is found, the correct decision cannot be made. |
| Unlicensed driving | Some township ship drivers are driving ships without a license and sailing in violation of the regulations. |
2.4 Management factors
Management factors are mainly reflected in crew management and system management.

(1) Crew management is an important cause of collisions between ships and navigation marks. The crew management factors include the inadequate implementation of the tasks, the evacuation of responsibilities by the management personnel, and some crew members have not even received professional training and have no understanding of ship navigation rules such as ship collision avoidance rules and watchkeeping rules. Secondly, the crews of shipping companies are highly volatile, and the ship's pilots lack a certain degree of work stability, resulting in the crews' lack of sufficient understanding of the performance of the ship they are driving, poor operating techniques, and there are many hidden dangers that affect the safe navigation of ships.

(2) System management includes that the waterway management department is not timely in patrolling the navigation marks, and the patrolling personnel lack sufficient awareness of safety responsibilities. The management department should improve the aging and damaged navigation marks in accordance with the navigation conditions and regulations in a timely manner. The unclearly marked navigation marks shall be replaced in time.

3. Solution
Based on the above analysis of the reasons for ship collision with navigation marks, this paper has designed an intelligent navigation marks anti-collision warning method from the navigation marks themselves. Due to the current situation that AIS marks are not fully popularized at present, using AIS to determine the distance between the ship and the marks has certain limitations. In addition, the accuracy of shipboard AIS equipment for ship's position information needs to be improved, which is difficult to meet the requirement of anti-collision navigation marks for distance accuracy between ship marks. Requirements for the accuracy of the distance between ship marks. Therefore, this paper uses passive underwater acoustic detection technology to complete the distance measurement between the navigation mark and the ship. When the information processing module detects that the distance between the ship and the navigation mark is less than the set value, the warning light mounted on the navigation mark is activated to flash the alarm, and the navigation data transmission module immediately sends a collision warning to the AIS information center in the form of a message. In turn, the AIS information center issues a VHF voice alarm to the dangerous ship in the water area where the warning mark is located.

3.1 Overall structure of anti-collision mark
The anti-collision navigation mark carries the passive underwater acoustic detection device at the bottom of the navigation mark, measures the distance of the ship through the underwater acoustic detection module, and transmits the distance signal to the information processing module. When the information processing module detects that the distance between the ship and the navigation mark is less than the warning distance At the same time, the warning light mounted on the navigation mark is activated to flash the alarm, and the navigation mark data transmission module immediately sends a collision warning to the AIS information center in the form of a message. The information center can find the dangerous ships in the water area where the warning mark is located through the AIS system, and then use VHF communication to give a voice alarm to the dangerous ships. This scheme can enable dangerous ships to find the dangerous state in time and make emergency operations to avoid collisions between ships and navigation marks. The structure of the anti-collision navigation mark and the anti-collision process of the navigation mark are shown in Figures 1 and 2.
3.2 Overview of passive underwater acoustic detection technology

Passive underwater acoustic detection receives the noise generated by the movement of the ship through the underwater acoustic transducer, and calculates the time when the underwater acoustic transducer acquires the noise to obtain the position and distance of the ship relative to the navigation mark. Passive underwater acoustic detection technology is mainly divided into the following three types: ternary sub-array ranging, matching field processing, and target motion analysis.

Three-element sub-array ranging, because the distance of each element from the observation target is different, so there is a certain time delay for the sound generated by the observation target to be transmitted to each element. The distance and the time difference between the sound reaching each sub-array can be used to solve the observation target azimuth and distance.

Matching field processing, this method collects sound field data of the sound source and environment around the experimental object, which requires high accuracy of environmental parameters. The basic principle is to determine the distance and depth of the maximum correlation by comparing the correlation between the measurement field and the copy field[7].

For moving target analysis, this method is a relatively mature long-distance ranging method, but in actual observation, the observation accuracy of this method is greatly affected by the number of observations, that is, when the number of sound signals acquired by the underwater acoustic transducer is less, the error of the solution observed by this method is large. When the number of sound signals...
acquired is large, the solution error of this method is significantly reduced. Therefore, this method is suitable for long-time observation scenarios[8].

Compared with the advantages and disadvantages of the above three schemes and combining with the special working state of the navigation mark, this paper uses the ternary sub-array ranging method to complete the distance calculation between the navigation mark and the ship.

3.3 Principle of ternary subarray ranging
In the ternary sub-array ranging, the distance measurement and direction finding based on the ternary symmetric array are the easiest. It uses three sub-arrays arranged at equal intervals on the same straight line, and makes the middle sub-array coincide with the origin of the coordinate. By establishing a ternary symmetric matrix model, and then deriving the directional and ranging formulas of the ternary sub-array, the measured data can be obtained. The position and distance of the measured ship relative to the navigation mark can be obtained. Ship-to-mark distance measurement is shown in Figure 3.

Assuming that the ship under test is a point source, the noise generated by the ship under test propagates in the form of spherical waves. The ternary symmetric array ranging model is shown in Figure 4. Set three sub-arrays with equal spacing on the same straight line, the mutual spacing is $d$, the middle sub-array coincides with the coordinate zero point, from right to left, the three sub-arrays are defined as $S_1$, $S_2$, $S_3$, the distance of the three sub-arrays is measured. The distances are $r_1$, $r_2$, $r_3$. Measure the distance $r$ and azimuth $\alpha$ of the intermediate sub-array $S_2$ and the target ship $T$, and the speed of noise propagating in the water is $v$.

The polar coordinates are established with the origin of $S_2$ coordinates. The polar coordinates of the target ship are $T(r, \alpha)$, and the polar coordinates of the three sub-arrays are $S_1(d,0), S_2(0,0), S_3(d,\pi)$. According to the theorem of cosine.
\[
\begin{align*}
  r_1^2 &= r_2^2 + d^2 - 2r_2d \cos \alpha \\
  r_3^2 &= r_2^2 + d^2 - 2r_2d \cos(\pi - \alpha)
\end{align*}
\]  

Organized as
\[
\begin{align*}
  r_1 &= \sqrt{r_2^2(1 + \frac{d^2}{r_2^2} - \frac{2d \cos \alpha}{r_2})} \\
  r_3 &= \sqrt{r_2^2(1 + \frac{d^2}{r_2^2} + \frac{2d \cos \alpha}{r_2})}
\end{align*}
\]

Suppose the time when the noise generated by the target ship travels to the three sub-arrays is \( \tau_1, \tau_2, \tau_3 \) in this order.

\[
\begin{align*}
  \tau_{12} &= \tau_2 - \tau_1 \\
  \tau_{23} &= \tau_3 - \tau_2 \\
  \tau_{13} &= \tau_3 - \tau_1 = \tau_{12} + \tau_{23}
\end{align*}
\]

In Equation 3, \( \tau_{12} \) is the time difference between the ship noise ship and the sub-arrays \( S_1 \) and \( S_2 \), \( \tau_{23} \) is the time difference between the ship noise ship and the sub-arrays \( S_2 \) and \( S_3 \), and the time difference \( \tau_{23} \) between the sub-arrays \( S_1 \) and \( S_3 \) is the difference between \( \tau_{12} \) and \( \tau_{23} \) with.

\[
\begin{align*}
  r_2 - r_1 &= v(\tau_2 - \tau_1) = vr_{12} \\
  r_3 - r_2 &= v(\tau_3 - \tau_2) = vr_{23}
\end{align*}
\]

Substituting equation (2) into equation (4), we get

\[
\begin{align*}
  r_2 - \sqrt{r_2^2(1 + \frac{d^2}{r_2^2} - \frac{2d \cos \alpha}{r_2})} &= vr_{12} \\
  \sqrt{r_2^2(1 + \frac{d^2}{r_2^2} + \frac{2d \cos \alpha}{r_2})} - r_2 &= vr_{23}
\end{align*}
\]

In formula (5), \( r_2 = r \), move the term of formula (5) to the left and right, square the two sides, and get

\[
\begin{align*}
  2r &= \frac{v^2 \tau_{12}^2 - d^2}{vr_{12} - d \cos \alpha} \\
  2r &= \frac{d^2 - v^2 \tau_{23}^2}{vr_{23} - d \cos \alpha}
\end{align*}
\]

Substituting equation (6) into equation (7), the expression of \( \cos \alpha \) is

\[
\cos \alpha = \frac{d^2 \tau_{13}v - v^3 \tau_{12} \tau_{23} \tau_{13}}{2d^3 + dv^3 \tau_{23}^2 - dv^2 \tau_{12}^2}
\]

From the concept of inverse function, the azimuth \( \alpha \) of the measured ship relative to the navigation mark can be expressed as

\[
\alpha = \arccos \frac{d^2 \tau_{13}v - v^3 \tau_{12} \tau_{23} \tau_{13}}{2d^3 + dv^3 \tau_{23}^2 - dv^2 \tau_{12}^2}
\]
Subtracting equation (10) and equation (11), the distance \( r \) between the ship and the navigation mark can be estimated as

\[
2r \cos \alpha - 2d = v^2 - d^2
\]

\[
2r \cos \beta - 2d = d^2 - v^2 \tau_{23}^2
\]

Subtracting equation (10) and equation (11), the distance \( r \) between the ship and the navigation mark can be estimated as

\[
r = \frac{v(\tau_{12}^2 + \tau_{23}^2)}{2(\tau_{12} - \tau_{23})} - \frac{d^2}{v(\tau_{12} - \tau_{23})}
\]

### 3.4 Anti-collision warning method

Passive ranging using a ternary symmetric array can achieve all-weather, low-energy, and high-precision measurement of the distance of the ship's mark. The information processing module is used to divide the area near the position of the navigation mark from far and near into collision prediction area and early warning intervention area. Part, and define the function of each monitoring area:

1. **Collision prediction area**: When it is detected that a dangerous ship enters this area, this mark data transmission module immediately sends a collision warning to the AIS information center in the form of a message. The information center can find the dangerous ships in the water area where the warning mark is located through the AIS system, and then use VHF communication to give a voice alarm to the dangerous ships;

2. **Early warning intervention area**: when it is detected that a dangerous ship enters this area, this mark simultaneously issues a voice alarm based on VHF communication and a flash warning based on early warning lights.

In this solution, multiple warning lights are installed at the bottom of the upper plane of the navigation mark, which can provide 360° all-round early warning around the navigation mark. The specific mounting position is shown in Figure 5. Because the navigation mark will be affected by wind and waves, it is in a rotating and swaying posture. Therefore, for the accuracy of the flash warning, the information processing module obtains the ship's position relative to the navigation mark through the ternary symmetry array. When the distance between the measured ship and the navigation mark is less than the set value, according to the ship's position relative to the navigation mark, the warning light of the corresponding position is activated. The early warning light not only avoids the energy waste caused by the omni-directional early warning lights flashing at the same time, but also avoids the visual impact on the normal moving ships. The flash warning effect is shown in Figure 6.

![Figure 5 Schematic diagram of the angle of the warning light](image-url)
Figure 6 Flash warning cab simulation

The very high frequency (VHF) communication system in this scheme uses the VHF dedicated frequency band for ship safety, emergency and distress communication, which is widely used in ship evasion, maritime management, port production scheduling, ship internal management, distress search and rescue, and safety information broadcast, etc. In terms of aspect, it is the main means of on-site communication for water transportation[9]. In addition, VHF communication has the advantages of being less susceptible to interference from other signals, low energy consumption, and low diffraction loss. According to the scope of application in the General Regulations of Part A of Chapter 4 of the International Convention for the Safety of Life at Sea (SOLAS), all passenger ships and cargo ships of 300 gross tonnage and above must install VHF radiotelephone communication equipment no matter in which sea area they are sailing. VHF communication has become an indispensable communication tool for ensuring the safety of ships and handling emergency situations at sea. The popularity of VHF communication equipment provides great theoretical support for the early warning method described in this solution.

4. Supply-Energy Analysis

4.1 Power consumption calculation

The intelligent anti-collision warning navigation mark designed in this paper mainly includes the following energy-consuming equipment, whose power is determined according to label reading and experiments, as shown in Table 2:

| Electrical Equipment                        | Daily energy-consuming equipment |
|--------------------------------------------|----------------------------------|
|                                           | Navigation mark control terminal | Early warning matrix lights (8) | Underwater acoustic transducer (3) | Communication module |
| Working current/mA                         | 167                               | 4160                           | 28                                  | 1200                   |
| Working voltage/V                          | 24                                | 12                              | 500                                 | 3                      |
| Power/W                                    | 4                                 | 50                              | 14                                  | 3.6                    |

In the system, except for the matrix lamp working voltage is the same as the system power supply voltage, the working voltages of other energy-consuming devices are different. Since the power supply voltage of the system is 12V, the efficiency of the step-down module used is $\eta_i=90\%$, which can be obtained. The total power consumed by the platform daily is:
among them:

Daily energy-consuming equipment (a navigation mark control terminal and communication module) work 24 hours, and its daily working time is 24 hours.

There are 3 underwater acoustic transducers. When the system is working normally, the nearby waters are detected 6 times within one minute. When a dangerous ship is detected, the underwater acoustic transducer is used for continuous detection; the matrix light is mainly responsible for flash warning. According to the software simulation, the working time of the underwater acoustic transducer is about 4h per day, and the working time of the warning matrix lamp is about 0.4h per day.

### 4.2 Calculation of power generation

The power generation is mainly calculated by the following formula:

\[ W_{\text{Power Generation}} = W_{\text{Solar Energy}} = \eta_2 AG, \]

Where: \( \eta_2 = 18\% \) is the conversion efficiency of the solar cell; \( A \) is the area of the solar panel/m\(^2\); is the total radiation on the solar panel.

\[ A = \pi \times 0.9^2 - \pi \times 0.1^2 = 2.512 m^2 \]

### 4.3 Comparative analysis

Since the scope of use of this base station is offshore waters, the parameters of the Bohai Sea area are taken as examples to calculate the power generation of solar power generation devices.

According to the statistics of the National Aeronautics and Space Administration (NASA), the total solar radiation in the Bohai Sea area in each month is shown in Table 3 below.

Table 3 Monthly total solar radiation in the Bohai Sea

| Month | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Solar radiation (KW⋅h/m\(^2\)) | 85.87 | 104.7 | 143.8 | 168.6 | 188.8 | 180.3 | 166.8 | 158.4 | 138.6 | 108.6 | 83.42 | 75.02 |

According to Table 2, substitute the power generation calculation formula, calculate the monthly average power generation and convert it into the daily average power generation, and compare the results with the daily power consumption as shown in Table 4 and Figure 7.

Table 4 Total power generation and power consumption

| Month | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Solar radiation (KW⋅h/m\(^2\)) | 38.83 | 47.34 | 65.02 | 76.23 | 85.37 | 81.52 | 75.42 | 71.62 | 62.67 | 49.1 | 37.72 | 33.92 |
| Average daily power generation/kWh | 1.25 | 1.69 | 2.1 | 2.54 | 2.75 | 2.72 | 2.43 | 2.31 | 2.09 | 1.58 | 1.26 | 1.09 |
| Average daily power consumption/kWh | 0.409 | 0.410 | 0.408 | 0.409 | 0.410 | 0.408 | 0.411 | 0.409 | 0.410 | 0.411 | 0.407 | 0.409 |
Figure 7 Comparison of average daily power generation and power consumption

5. Conclusion
Energy supply through intelligent anti-collision avoidance warning navigation mark-energy consumption analysis, it can be found that the daily power generation of this navigation mark is far more than the power consumption. At the same time, the rich power can be filled with lithium iron phosphate batteries, which guarantees the daily work of this navigation mark, provides stable power support for the work of various parts of the navigation mark. An intelligent anti-collision warning method for navigation aids proposed in this paper uses a three-element sub-array to measure the distance between navigation aids and ships. When the information processing module detects that the distance between the navigation aids is less than the set value, the dangerous ship will be flashed and warned. VHF voice alarm can give full warning to dangerous ships, avoid the occurrence of ship collision with navigation marks, and ensure the safety of maritime navigation.

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References
[1] Li Wenfeng, Chen Zhihui. Forecast and Analysis of the Number of National Coastal Navigation Marks Based on Grey Markov[J]. China Water Transport (the second half of the month), 201717(10): 126-127+133.
[2] Li Zhong. On the idea of color and shape of floating signs at night[J]. Pearl River Water Transport, 2019(18):79-81.
[3] Zheng Youpeng. Thoughts on the application of CCTV monitoring equipment in navigation mark management[J]. China Water Transport (the second half of the month), 201919(11):101-102.
[4] Wang Ying, Ouyang Wenquan, Zhao Jian, Chen Jia. The application of ship anti-collision warning video monitoring technology in the Huaihe waterway[J]. China Water Transport (second half of the month), 201818(02):51-52.
[5] Feng Xiangchao, Research on collision detection device of marine hydrological monitoring buoy, Shandong University of Science and Technology, 2016.
[6] Zhou Sihong, Research on Anti-collision Countermeasures for Navigation Marks, 2018 Maritime Management Academic Annual Conference, Changchun, Jilin, China, 2018, p. 4
[7] Luo Xinyu, Hao Qingshui, Cao Jianmei, Han Qingbang, Li Jian. Simulation research of pattern matching method for underwater target positioning[J]. Microprocessor, 201637(1): 68-71.
[8] Ju Yang, Yuan Yonghu, Lin Wei, Xu Haisheng. Analysis and solution of fast target motion with uniform acceleration based on acoustic information[J]. Acta Armamentarii, 201940(8):1688-1692.
[9] Liu Guoliang. Marine very high frequency (VHF) communication and precautions for use[J]. Navigation Technology, 2009(4): 45-46.