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COLLISION WARNING SYSTEM FOR SMALL MARITIME AUTONOMOUS SURFACE SHIPS

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Key words: AIS, wireless access in vehicular environment (WAVE) communication, collision warning system, maritime autonomous surface ship (MASS).

ABSTRACT

In this study, wireless communication technologies used in road and marine traffic are compared and analyzed to develop a collision warning system for small maritime autonomous surface ships based on sufficient testing and technologically advanced wireless access in vehicular environment (WAVE) communication technology. Outstanding communication technologies, such as WAVE, have been used as the core technology for the infrastructural development of an intelligent transport system (ITS) as well as autonomous vehicles in many countries and industries. In WAVE communication, information is transmitted in 100-ms intervals. Therefore, it is feasible to maintain control of ships by fully supplementing the update interval of small automatic identification system (AIS) Class B ships using an autonomous navigation system for small ships, thus establishing a safe autonomous navigation system. Additionally, as information is retransmitted every 0.1 s, such a system can sufficiently handle sudden and unexpected risk situations encountered by small ships such as fishing boats.

To evaluate the appropriateness of the proposed collision warning system based on WAVE communication, real ship tests were conducted for a comparative analysis using AIS communication-derived results. Based on the real ship test results, calculations were appropriately conducted according to the criteria of collision warning determination when confronting dangerous collision situations. In particular, systems based on AIS were found to often miss collision warnings owing to frequent variations in small ships. However, systems based on WAVE were found to have detected all collision risks.

I. INTRODUCTION

1. Background

Autonomous ship navigation will inevitably be developed and deployed. According to the international maritime organization (IMO), autonomous ship navigation is divided into four stages. Stage 3, in which no crewmembers are on board to achieve full remote control, and Stage 4, which corresponds to fully autonomous navigation, are stages in which the system controls all processes of a ship. In these stages, a machine rather than a human determines the risk of collision (IMO, 2018; Jung et al., 2019). Consequently, it is possible that control issues, such as system errors and communication disconnections, may lead to severe marine accidents.

Studies on autonomous ship navigation have shown that navigation safety systems, such as ship collision prevention systems, are mostly intended for ships of a particular size or large ships (Levander, 2017). These ships are equipped with advanced devices such as electronic navigational charts, and their voyage-supporting systems are based on these devices. However, small ships such as fishing boats are equipped only with an automatic identification system (AIS) owing to economic constraints, and collisions most frequently occur among small ships, such as fishing boats. Consequently, there is an urgent need to develop technologies for preventing collisions of small ships (Kang et al., 2019).

AIS communication systems used in small ships have recently been concerned with communication-traffic-related issues. Class B AIS communication, which is used in fishing boats, transmits information every 30 s (Zhang et al., 2018). A signal obtained from AIS communication traffic cannot provide immediate information to a navigator in cases requiring immediate action to avoid the risk of collision because it is transmitted every minute. Harati-Mokhtari et al. (2007) conducted research to accurately evaluate AIS data. Investigation results of AIS errors considering service conditions indicated that 30% of ships were incorrectly analyzed. Moreover, data noise was observed in the location information of the AIS data similar to that found in global positioning system (GPS) data. Owing to these limitations of AIS, it cannot be regarded as a

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viable mean of communication. Because AIS is no longer considered an appropriate communication technology for autonomous ship navigation, alternative technology must be developed.

Many studies and pilot projects have been conducted by road traffic authorities to develop and implement vehicle communication technology before initiating the development of autonomous driving automobiles (Muhammad and Safdar, 2018). Such a vehicle communication technology is referred to as vehicle to everything (V2X), which was developed as the core technology for autonomously driven automobiles. Wireless access in vehicular environment (WAVE) communication technology is a representative of approved V2X communication technologies. It is equipped with outstanding information security without additional expenses. Thus, WAVE communication technology is appropriate for traffic environments.

In this study, a collision alert system for small ships based on WAVE communication technology was developed as fundamental research toward the development of autonomous navigation collision alert systems for small ships. The proposed system consists of data-receiving, computing, collision risk determination, and display sections. This system was implemented in an actual ship for testing. To validate the appropriateness of the proposed system, a comparative analysis was performed using existing AIS communication system.

2. Related Studies

Ship tracking information represented by AIS data in an important data source for ship collision research. AIS data can monitor the movements of approaching ships and improve navigation safety using collision avoidance models or systems (Li et al., 2012; Mazaheri et al., 2016).

Zhang et al. (2018) suggested a multiregime vessel trajectory reconstruction model involving a three-stage process to ensure the accuracy of existing AIS data that contain noise. In this model, a vessel's trajectory was reconstructed based on the circumstances of each ship. The suggested model based on an AIS dataset obtained from a large port was tested in comparison with linear, polynomial regression, and weighted regression models, yielding favorable results.

For collision avoidance of autonomous surface ships, Chiang and Tapia (2018) proposed an RRT (Rapidly-exploring Random Tree)-based motion planning method with COLREG compliance. Zhao et al. (2019) developed a novel deep reinforcement learning algorithm to improve the effectiveness and efficiency of tracking ship routes and a collision prevention system for autonomous ship navigation.

Regarding algorithms for collision avoidance systems, many researchers have used the artificial potential field (APF) concept for automatic navigation planning and collision avoidance in marine traffic (Xue et al., 2011; Xiao et al., 2012; Rong et al., 2015). The basic concept of APF is to fill the operating space with an APF to guide the ship to a gradient of potential for obstacle avoidance and drive it to the target point. Alternatively, Lee et al. (2019) proposed algorithms for automatic collision avoidance and ship route generation. The suggested automatic collision avoidance system contained course-changing and track-maintaining modes based on the velocity potentials of the vortex and dipole flow theory, respectively. To verify the suggested methods, simulations based on the performance of the velocity potential field model were performed using the ship navigation and collision avoidance algorithm. The collision avoidance algorithm was implemented using distance at the closest point of approach (DCPA), time at the closest point of approach (TCPA), and real bearing angle data from ship navigation simulation. Simulation results showed that the suggested methods successfully avoided collision. Moreover, the velocity potential field model proved to be appropriate for the suggested automatic collision avoidance algorithm.

Kang et al. (2018b) adopted the ship domain as a criterion for the estimation of collision avoidance. Additionally, using a particle swarm optimization algorithm, an optimal route plan was established without the risk of ship collisions in a real-time navigation environment. COLREG-compatible simulations based on voyage scenarios that involved confronting fixed obstacles showed positive results.

In previous research on collision avoidance and path tracking, a collision was automatically avoided and the ship returned to the planned routes. However, these methods require updating the location of the ship regularly. In particular, a small ship is not provided with a specific route. Therefore, autonomous ship navigation technology must be developed for small ships, such as fishing boats. Further, the implementation of AIS is challenging, which is most frequently used in autonomous ship navigation devices of small ships, in accordance with the characteristics of the system. Consequently, new concepts in communication technology must be established to address these issues.

In this study, the characteristics of small ships are analyzed and a collision avoidance system based on a communication service is developed to achieve autonomous navigation of small ships. The research scope is limited to determining the risk of collision and notifying the navigator whether detour is necessary.

II. ANALYSIS OF CHARACTERISTICS OF SMALL SHIPS FOR AUTONOMOUS NAVIGATION

1. Navigation Analysis of Small Ships

Small ships such as fishing boats freely navigate in deep water with a substantial risk of sudden and unexpected collision that requires sudden veering and navigation speed adjustment. Furthermore, because there are limited crewmembers on board, the system must be equipped to immediately notify the navigator of the possible risk of collision, as crewmembers tend not to watch the circumstances carefully.

Small ships are typically equipped with AIS instead of cutting-edge navigation systems for economic and other reasons.

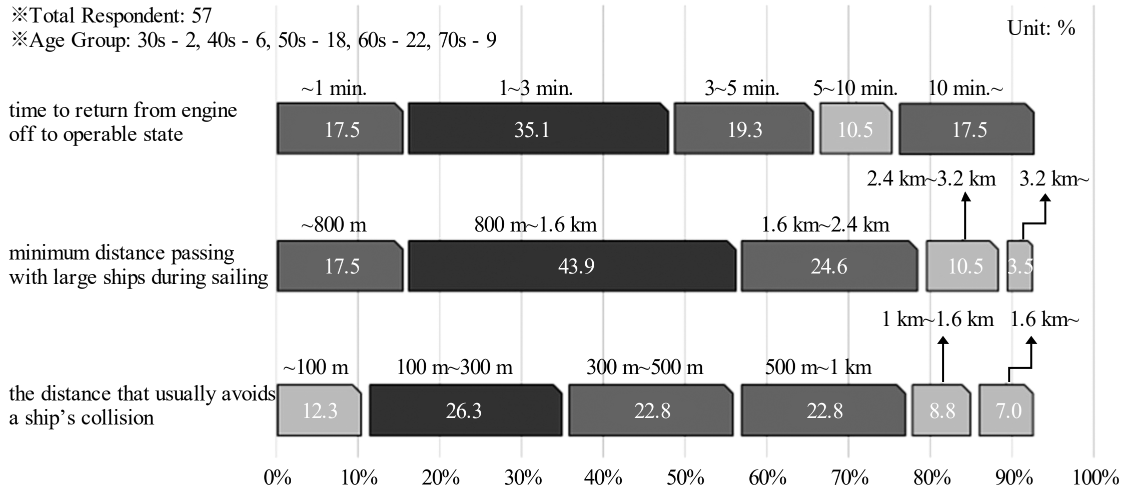

Fig. 1. Results of a survey conducted on small-ship navigators

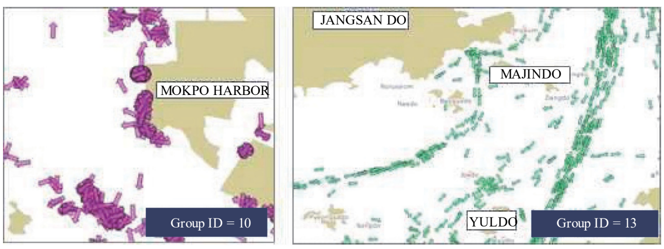

Fig. 2. Example of trajectory classification (Oh et al., 2018)

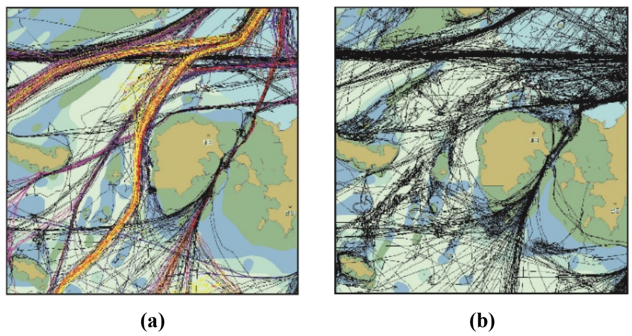

Fig. 3. Trajectories of ship's traffic

Class B is the most useful type of AIS in fishing boats. AIS is classified into Class A and Class B. Class A provides assistance in complying with IMO equipment requirements. Class B provides lower performance and grading standards than Class A, thereby reducing the burden on the AIS network and making it available for use in small ships to reduce economic hardships (Xiao et al., 2015).

In Class B AIS communication technology, dynamic information, such as the ship location, is transmitted at an interval of 30 s. If a signal transmission fails owing to the communication environment, information is transmitted once every minute. An imminent risk of collision before updating the AIS information can increase the difficulty supporting the navigator adequately. Moreover, an increasing trend of ships equipped with AIS and the application services of AIS have created a problem regarding increased communication traffic. Consequently, AIS signals are frequently missed.

Fig. 1 shows the results of a survey conducted on navigators navigating their fishing boats near the sea at Yeongheung-do. A distance of 100–300 m was typically maintained to avoid collision, with 26.3% and 22.8% of respondents maintaining a distance of 300–500 m and 500 m–1 km, respectively. Consequently, the distance maintained by fishing boats to avoid a collision was considered to be 100 m–1 km.

Based on the speed of a ship, the forwarding distance was approximately 308 m per minute at 10 kts and 617 m per minute at 20 kts. According to the survey reported in Fig. 1, a collision avoidance or alert system that does not update the ship location or movement up to approximately 617 m per minute cannot provide accurate information to a navigator despite the risk of collision.

2. Analysis of Navigation Characteristics of Small Ships

Oh et al. (2018) identified ships moving abnormally by detecting unusual circumstances of a ship moving in or out of a port. Fig. 2 shows some results of subclassifying a group of ships by analyzing and learning the pattern of the ship navigating around Mokpo harbor and identifying ships moving abnormally. In this study, the navigation patterns of ships moving normally were learned using clustering accumulated navigation data, which were compared with a normal learning model to distinguish ships moving abnormally.

Oh et al. (2018) showed that it is possible to automatically identify abnormal ship conditions using navigation data and machine learning. However, this approach is limited to ships with specific navigation patterns. The route of a small ship is generally unstable, including fishing boats. Establishing navigation patterns for a destination with almost no restriction

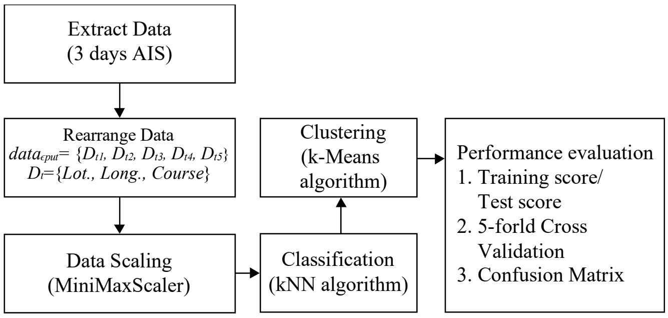

Fig. 4. Block diagram of the traffic pattern clustering process

on water depths does not involve specifying details such as the veering point and angle. Consequently, ships do not navigate in the same routes even if they are heading to the same destination but slightly change their routes depending on circumstances (Lee and Kim, 2019).

In Fig. 3(a), the merchant ships navigate the ocean with a consistent pattern on the planned routes. Conversely, fishing boats follow their routes, as shown in Fig. 3(b), but also navigate freely in the entire range of the ocean. Additionally, fishing boats move in a zig–zag fashion on particular routes depending on their purpose.

In this study, navigation patterns of fishing boats are learned in a manner similar to those of previous studies. A learned navigation model was established using merchant ship data learning to analyze the characteristics of small ships, such as fishing boats, to determine the feasibility of clustering and classifying navigation patterns. Fig. 4 shows the navigation pattern learning model.

The first stage is the extraction of learning data. As this step is performed to obtain an approximate determination of whether it is feasible to classify navigation patterns, AIS data were extracted with three unities and used as target data. Because data were received randomly, they were classified into five types based on the order in which they were received. Three types of data, namely, latitude, longitude, and course, were grouped into one set according to their order time, as shown in the formula below, using five datasets in total. A total of fifteen-dimensional data were generated and used.

$$data_{\in put} = \{D_{t1}, D_{t2}, D_{t3}, D_{t4}, D_{t5}\} \tag{1}$$

$$D_t = \left\{ \begin{array}{c} La_t, Lo_t, C_t \\ \Delta La_t, \Delta Lo_t, \Delta C_t \end{array} \right\} \tag{2}$$

$$where, La: latitude, Lo: longitude,$$
$$C: Course\, of\; ground$$

The extracted AIS data are shown in Fig. 5.

The next stage involves the clustering of data with similar navigational characteristics. Clustering was performed using the k-means algorithm. This algorithm clusters data into k

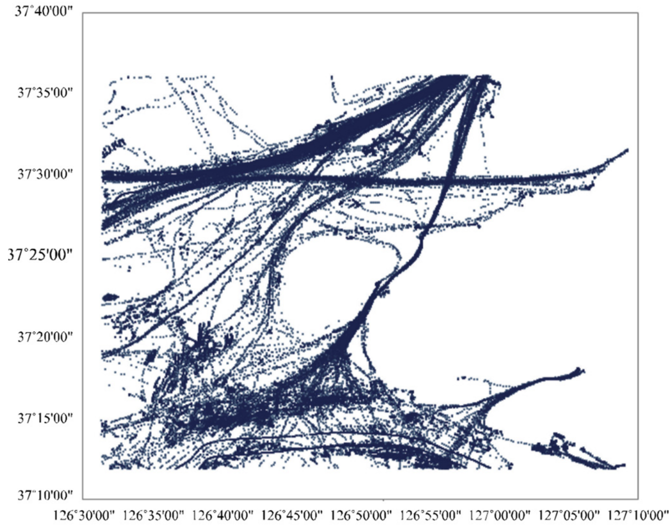

Fig. 5. Ship trajectories for AIS data (three days) in the target area

categories to minimize the deviation of the distance difference with each cluster. As a part of machine learning classified as autonomous learning (noninstructional learning), the k-means algorithm assists in applying labels to previously unlabeled input data. The k-means algorithm has a clustering structure that is similar to that of the expectation–maximization algorithm, with estimates of simulation, including maximum likelihood or maximum probability, in the probability model that relies on potential variables (Varuna and Natesan, 2015; Sun and Shyue, 2017; Zhen et al., 2017).

For a set of $d-$ dimensional data observations $(x_1, x_2, \cdots, x_n)$, the k-means algorithm partitions $k(\le n)$ data sets of n data observation to maximize the cohesion between observations in each set, $S = \{S_1, S_2, \cdots, S_k\}$. The total variance is calculated using formula (3), where μ_i is the center of the i^{th} cluster and S_i is the set of points belonging to the cluster.

$$V = \sum_{i=1}^{k} \sum_{x \in S_i} \|x - \mu_i\|^2 \tag{3}$$

The objective of this algorithm is to determine S_i that minimizes this value.

In the next stage, the k-nearest neighbor (KNN) algorithm is used to classify the clusters according to each status. The KNN algorithm uses the k-nearest data. This algorithm is a very intuitive method for classifying samples not classified according to similarity. If samples have no specific classification, the algorithm finds the k-nearest samples from learned data and assigning them to a group with the highest frequency. The KNN algorithm can be used only if the constant, k, classified learning data, and the distance criteria are all available (Duca et al., 2017; Damastuti et al., 2019).

After these procedures are completed, the model is evaluated

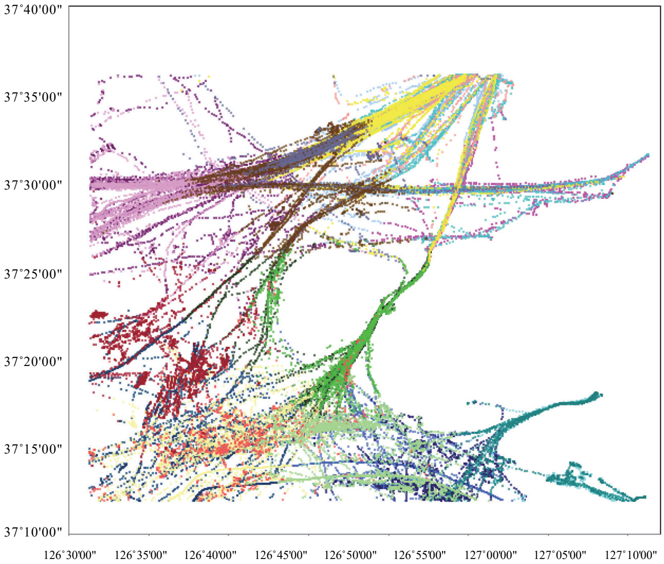

Fig. 6. Ship trajectories for clustering AIS data (three days)

to verify its performance. Fig. 6 shows the results of floating each of the clustered data after clustering is performed. Different colors are used to represent each cluster, and results showed that the clusters of data were not meaningful.

III. DEVELOPMENT OF THE COLLISION ALERT SYSTEM

AIS uses a VHF frequency, and Class B transmits dynamic information of a ship every 30 s. However, because autonomous ship navigation is continuously controlled, the data transmission time of the location between the main ship and other ships is very important. If data are updated every 30 s or one minute, as currently updated, it is difficult to ensure safety in autonomy in ships that are controlled by a system.

In this section, WAVE communication, a V2X technology used as the core technology in autonomously driven vehicles, is analyzed to provide the criterion for developing an appropriate collision avoidance alert system for autonomous small ship navigation.

1. Analysis of WAVE Communication

WAVE communication technology is a communication standard by the Institute of Electrical and Electronics Engineer (IEEE) in the US. Its standard frequency is in the bandwidth of 5.9 GHz. In the US or Europe, up to 1 km of transmission distance is required along with a high-speed moving environment of 200 km/h and up to 27-Mbps data transmission speed. Moreover, this technology satisfies the basic performance goal with a short packet speed of less than 100 msec. With the advancement in communication technologies, there is a need to change the existing intelligent transport system (ITS) environment. Subsequently, IEEE 802.11p, which was modified from Wi-Fi-based IEEE 802.11a, was designated as the standard for

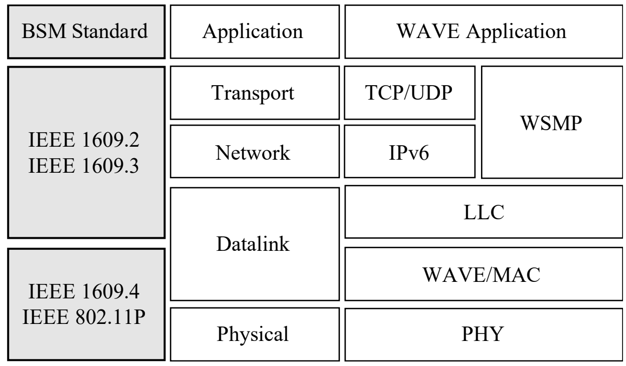

Fig. 7. WAVE communication protocol

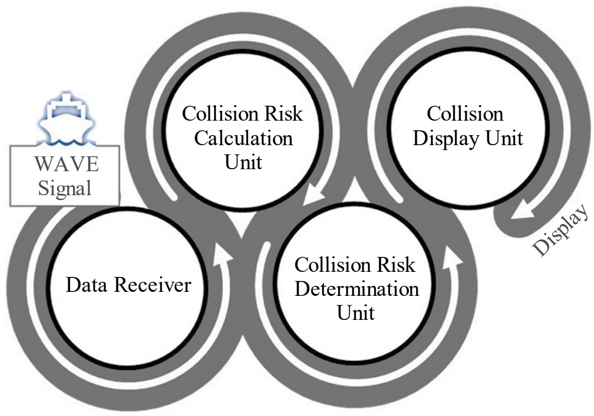

Fig. 8. Conceptual diagram of the proposed collision alert system

vehicle communication. Additionally, IEEE 1609 with characteristics such as resource management, security, and networking service was combined with IEEE 802.11p for emerging WAVE communication (Park, 2018).

Fig. 7 shows the WAVE communication protocol. The WAVE specifications include IEEE 802.11p, which defines the physical layers and specifications of the medium access control layers, and IEEE 1609, which defines the network, application, and security specifications. As an exclusive vehicle communication standard, IEEE 802.11p technology was partially modified from 802.11a specifications. Vehicle communication standards were established as a combination of the IEEE 802.11p and IEEE 1609.x specifications (Jiang et al., 2006).

Based on such standards, V2X communication technology and applied service were established in cooperation with the US, Europe, and Japan, who are commercializing them to provide the next-generation intellectual traffic information system and service (Voronov et al., 2015; Jeong et al., 2017).

WAVE communication provides outstanding characteristics such as transmission period, data speed, and security. It supports communication between a ship and infrastructure, as well as between ships. WAVE communication is an outstanding communication technology and available free of charge. Consequently, it is the appropriate communication technology

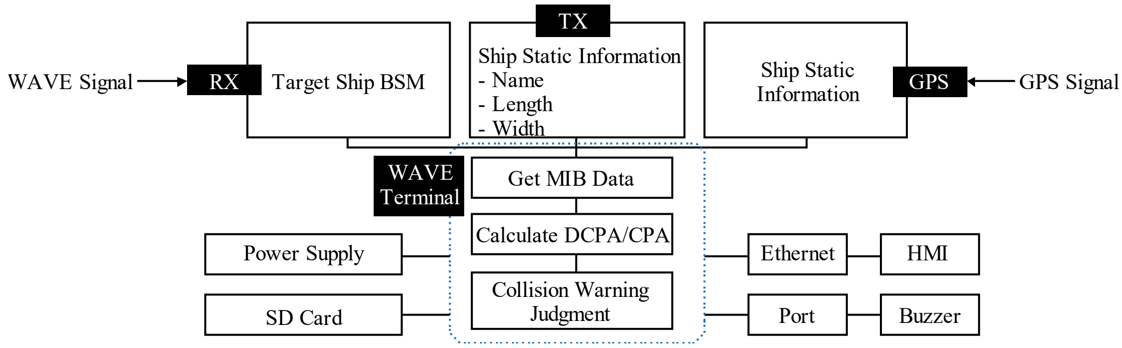

Fig. 9. Block diagram of the collision alert system based on WAVE communication technology for small vessels

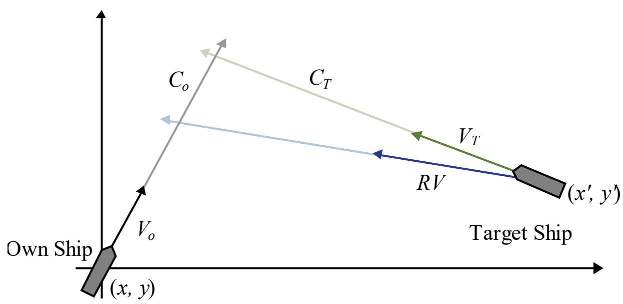

Fig. 10. Calculation of DCPA and TCPA

Table 1. Comparison of WAVE and AIS

Category	WAVE	AIS
Frequency	5.8 GHz	161.975 MHz 162.025 MHz
Communication Access Type	OFDM, CSMA-CA	SOTDMA, CSTDMA
Power	Less than 100 mW	2 W–12.5 W
Transmission Period	100 ms	30 sec (Class B)
Transmission Distance	Max. 5 miles	Max. 50 miles
Security Method	IEEE 1609.2	-

for small ships, such as fishing boats. Furthermore, WAVE communication technology updates dynamic information every 0.1 s. Consequently, it allows for sufficient preparation for a risk of imminent collision in small ships through rapid mutual communication between ships.

2. System Overview

The collision avoidance system developed herein consists of receiving, computing, determination, and display sections. Fig. 8 shows a conceptual diagram of the proposed system.

Fig. 9 shows a block diagram of the collision avoidance system based on WAVE communication technology for small vessels. In the receiving section, a basic safety message (BSM), such as the ship name, type, length, location, and speed, is received from multiple ships within the range of WAVE communication. In addition, a management information base (MIB) is configured according to the received information, such as ship information or GPS location entered in the memory (NAND). In the computing section, the risk is calculated following DCPA and TCPA. Information is provided to the collision alert display section after determining whether there is a risk of collision based on the pre-entered criteria of a collision alert according to the calculated DCPA and TCPA values. In this section, a warning signal is released through a human–machine interface or buzzer in such a manner that the navigator can perceive it.

3. Risk Determination Algorithm

Kang et al. (2018) conducted research on WAVE communication using road traffic applied to sea by measuring the available communication distance based on real ship experiments. WAVE communication technology from road traffic applied to sea can stably transmit or receive data up to 8–9-km distance measured using the line of sight. In addition, it is expected to provide accurate and various services at an affordable cost. Table 1 shows a comparative analysis of WAVE and AIS.

A risk determination algorithm for small ships was developed to secure the accuracy and reliability of the collision alert system when using WAVE communication technology as the principal means of communication. The initial determination distance was set to three miles (approximately 5.5 km), with an allowance of 3 km as the normal avoidance distance or detouring distance of ships within approximately 3 km.

The risk of collision was determined using DCPA and TCPA based on the consistency of spatial and temporal location between the main ship and other ships. Fig. 10 illustrates the concept and calculation of DCPA and TCPA (Kim, 2013).

$$RV_x = V_T \times \sin C_T - V_O \times \sin C_O \tag{4}$$

$$RV_y = V_T \times \cos C_T - V_O \times \cos C_O \tag{5}$$

$$\overrightarrow{RV} = \sqrt{(RV_x)^2 + (RV_y)^2} \tag{6}$$

$$TCPA = \frac{(x' - x) \times RV_x + (y' - y) \times RV_y}{\overrightarrow{RV^2}} \quad (7)$$

$$DCPA = \sqrt{D^2 - (\overrightarrow{RV} \times TCPA)^2} \quad (8)$$

(x, y): *Own Ship Coordinates*
(x', y'): *Target ship Coordinates*
V_O: *Own Ship Speed* (kts), V_T: *Target ship Speed* (kts)
C_O: *Own Ship Course* $(°)$, V_T: *Target ship Course* $(°)$
$\overrightarrow{RV}$: *Relative Vector*, D: *Distance between ships* $(miles)$
(RV_x, RV_y): *RV Coordinates*

The DCPA distance for the detour action differs according to the ship characteristics, such as ship size or speed, or sea characteristics, such as open sea, littoral sea, or areas near a port. For large ships, the detour action is performed using appropriate DCPA and TCPA values. However, the detour action is performed by small ships than by large ships. Moreover, the place where the antenna is attached becomes a criterion for determining DCPA and TCPA for the ship location. Moreover, the error range differs depending on the ship size.

This study aims to develop a collision avoidance system that is accurate and reliable for small ships, such as fishing boats. Further, the collision determination criteria are established in more detail.

DCPA determines the minimum distance allowed to minimize the occurrence of alarms not related to collision risks using the total length of the own ship and other ships.

TCPA is set to provide at least 2 min for warning from at least 1-km distance in consideration of the speed of fishing boats approaching each other headfirst. The navigation performance of ships equipped with ship control simulations is analyzed to verify the appropriateness of TCPA criteria. In addition, according to the results of surveys on navigators, the typical distance for collision avoidance was 100–300 m, with 26.3% and 22.8% respondents maintaining a distance of 300–500 m and 500 m–1 km, respectively. Moreover, more than 70% of the cases take action to avoid collision within 1 km of distance. Therefore, criteria with 2 min of TCPA became more reliable.

Furthermore, $\frac{L_a}{V_a} + \frac{L_b}{V_b}$ was used to calculate and add the distance from the edge of a ship to the antenna based on time. Moreover, because there might be a risk of collision either when a ship stops or is in operation, user input β was added to adjust the alert time if needed by users in consideration of ship circumstances.

The final DCPA and TCPA value criteria were obtained as follows.

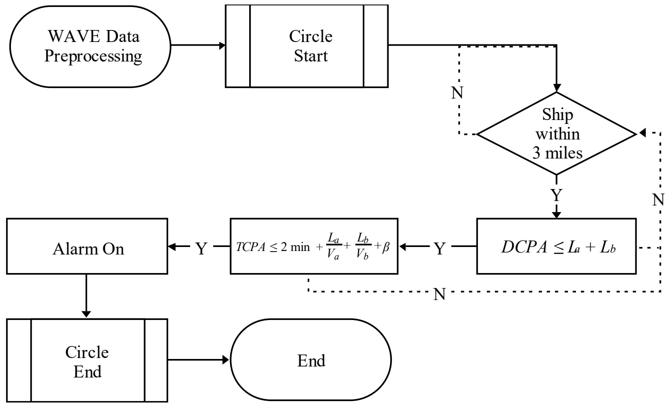

Fig. 11. Collision Warning Judgment Process

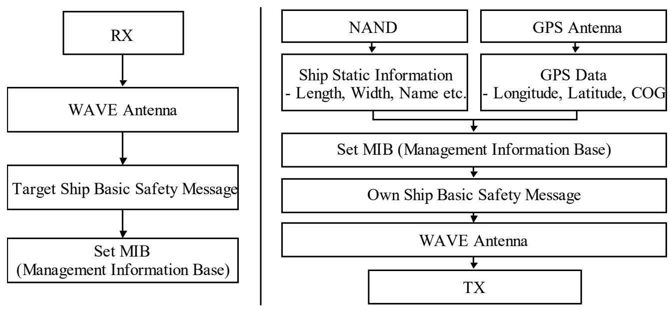

Fig. 12. RX and TX protocol

$$\begin{aligned} &DCPA \le L_a + L_b \\ &TCPA \le 2\,\text{min} + \frac{L_a}{V_a} + \frac{L_b}{V_b} + \beta \end{aligned} \quad (9)$$

The collision determination algorithm based on these criteria is shown in Fig. 11.

4. Receiving Section

In the data-receiving section, data of multiple other ships (RX), data of the main ship (TX), and GPS location of the main ship are received within the WAVE communication range.

Fig. 12 shows the RX and TX protocols.

5. Computing Section

In the computing section, DCPA/TCPA values are calculated based on the data received from the receiving section of each ship while determining whether there is a risk of collision and whether navigators must be alerted regarding a collision based on the collision alert determination criteria suggested in (9).

Fig. 13 shows the WAVE coding values in the collision risk-computing section.

To realize WAVE communication, software (SW) stacks such as the physical layers described in IEEE 802.11p and WAVE communication stacks described in IEEE 16092/3/4 are required. The collision risk calculation and risk determination algorithm is entered to the terminal using WAVE.

```
//os = own ship
//ts = target ship
Int Ship_algorithm(const CPA_t* cpa, const SHIPINFO_t* os, const SHIPINFO_t* ts)
{
    //convert ship length meter to nmile
    os_len = os ->length * MtoNM;
    ts_len = ts ->length * MtoNM;

    //ship length / ship speed
    os_spdlen = os_len / os ->spd;
    ts_spdlen = os_len / ts ->spd;

    //spdlen + custom input
    value = os_spdlen + ts_spdlen + os ->adjustment_value;

    //convert distance limit 3 nmile to meter
    distance_limit = 3.0 * NMtoM;

    //dcpa standard
    dcpa_standard = os_len + ts_len;

    //tcpa standard 2min
    tcpa_standard = 2.0;

    if(cpa->dist <= distance_limit)
    {
        if(0 <= cpa->dcpa) && (cpa->dcpa <= dcpa_standard)
        {
            if(0 <= cpa->tcpa) && (cpa->tcpa <= (tcpa_standard + value)
            {
                result = ALARM_DANGER;
            }
            else
            {
                result = ALARM_NULL;
            }
        }
        else
        {
            result = ALARM_NULL;
        }
    }
    return result;
}
```

Fig. 13. Input data for collision warning determination

6. Display Section

Collision risk determination is performed based on information regarding the main ship and other ships received in the receiving section. If the received information corresponds to $TCPA \le 2\min + \frac{L_a}{V_a} + \frac{L_b}{V_b} + \beta$, then it is provided to the collision alert display section to alert navigators.

The collision alert display section shows the collision risk information on the screen or provides the information to the alarm according to the alarm criteria based on the risk determination algorithm in the collision risk determination section. The collision alarm notifies the navigator of the risk of collision. A commercial alarm system product was purchased and used in this study because the alarm can be changed depending on the circumstances. The collision alarm used in this study uses a DC voltage of 12–24 V and maximum current of 0.980 A. Additionally, the frequency of the flickering LED was 60–80 per minute, with a maximum sound volume of approximately 115 dB.

IV. EXPERIMENTS USING REAL SHIPS

1. Experimental Overview

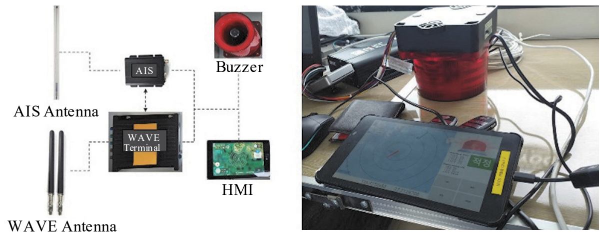

Fig. 14. Actual appearance of the collision alert system

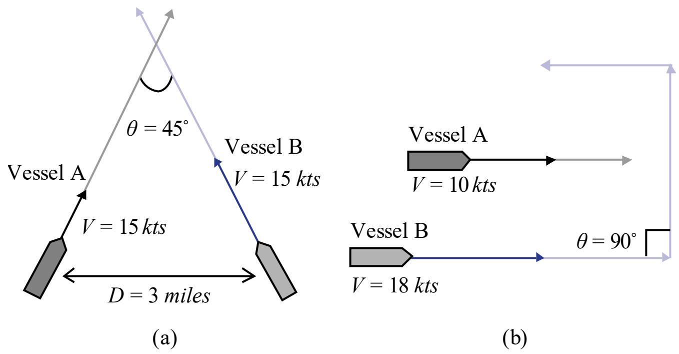

Fig. 15. Experimental scenario using real ships

The collision alert system used in this study uses WAVE communication as its principal means of communication. An experiment is conducted to compare the difference between AIS and WAVE communication systems using the collision alert system based on AIS.

Fig. 14 shows the actual system of the collision avoidance experiments with real ships.

BSM of other ships is received through AIS and WAVE antennas and transmitted to the WAVE terminal, along with the ship static information of the main ship. The WAVE terminal calculates and determines the risk of collision based on information on other ships and main ship and displays it to the outside of the terminal through buzzer and HMI.

The sea near Yeongheung-do was selected as the study area, where tens of casualties have occurred because of collisions of fishing boats and tankers in December 2017. The experiment is conducted on two fishing boats in operation in this area. Both the selected ships are 9.77 tons, and their lengths are 14.80 and 16.50 m. In the experiment, the maximum speed of the ships was 16 knots. At the time of the experiment, the wind speed and wave height were approximately 10–15 kts and 0.5–1.0 m, respectively.

2. Scenario

To verify whether the collision alert system functions correctly based on the risk determination algorithm in collision risk situations, scenarios were established by considering the navigation characteristics of small ships, such as fishing boats. Fig. 15 shows the experimental scenario using real ships to verify the collision alert system.

Ships A and B maintained 45° angle in the (a) scenario

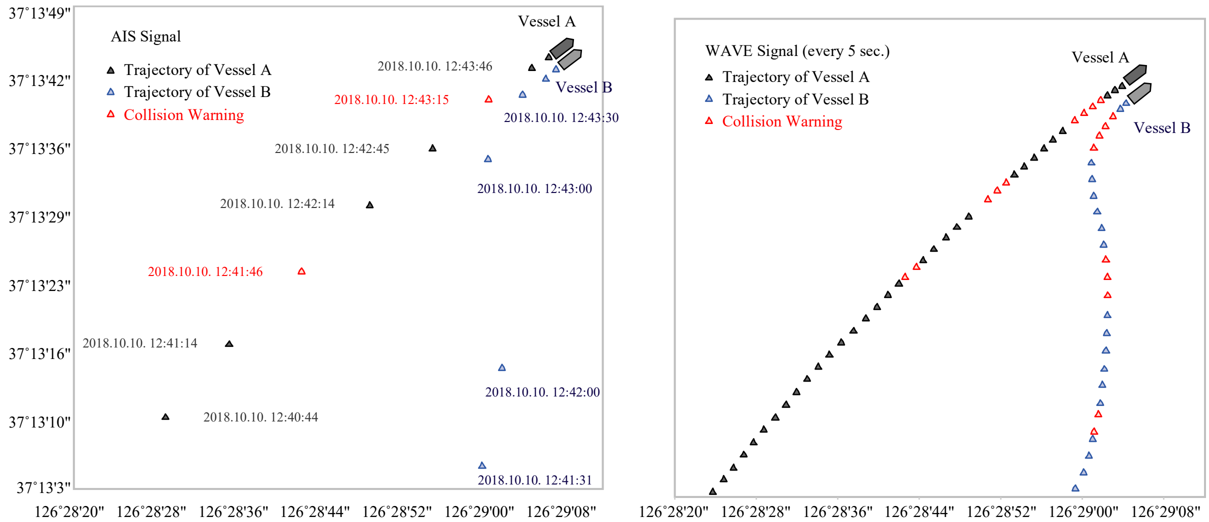

Fig. 16. Ship track of experiments based on real ship: scenario (a)

traveling toward the destination from a place that was approximately 3 miles away. In (b) scenario, ships A and B traveled forward while maintaining a certain distance. When ship A was ahead, ship A maintained a forwarding distance of 10 kts and ship B traveled at a forwarding distance of 19 kts to overtake ship A. When ship B was overtaking ship A sufficiently, ship B immediately veered at an opposite angle (approximately 90°) to travel past ship A.

3. Results of the Experiment on Real Ships

According to the results of the experiment on real ships, collision was correctly calculated and determined by the proposed system in case of collision risk situations. Moreover, risk collision information was appropriately provided to the navigator according to the assessment.

Fig. 16 presents the track and collision risk alert status obtained from the collision risk determination algorithm based on WAVE communication and AIS communication in scenario (a).

According to the characteristics of WAVE communication technology, information is transmitted at an interval of 100 ms. Therefore, it was evaluated that the system accurately detected the risk of collision from the instantaneously changing bearing of the other ship at a short distance and ship speed and delivered appropriate information to the navigator. For WAVE communication, the location information was renewed every 0.1 s. Therefore, if the location is indicated on the graph, it becomes an expression of a line. Hereafter, it is difficult to distinguish data individually. Therefore, Fig. 16 shows that the interval of transmission in the WAVE communication was changed to 5 s to extract the location information to be viewed on the track of the graph. Moreover, location information data retransmitted through AIS communication were duplicated on top of it comparing and analyzing the WAVE communication and AIS communication.

For AIS communication, approximately 30 s is required to transmit or receive information according to the characteristics of Class B communication. For ship A, the first location information was received on the graph at 12:40:44, followed by the information in approximately 30 s at 30, 32, 28, 31, 30, and 31 s. For ship B, the first location information was received at 12:41:31. Similar to ship A, the location information was received at approximately 30 s. However, the signal not transmitted owing to unknown causes in the middle of communication, because of which the next information was received after 1 min.

The system based on WAVE communication provided three collision risk alerts, even though two alerts occurred in ship A and no alert in ship B when the collision avoidance system was based on AIS communication. In particular, according to the ship track, ship B sailed for approximately 600 m per minute when the signal was not transmitted. When a ship sails at 15 kts, it normally travels forward at approximately 500 m per minute. Consequently, this ship cannot perform the appropriate collision avoidance action without an alert regarding the risk of collision being provided to the navigator, in contrast to ship B moving at approximately 500-600 m using the collision alert system based on AIS.

Fig. 17 shows the track of the ship based WAVE and AIS communications in scenario (b) and the alert status from the collision risk determination algorithm.

In Fig. 17, the transmission interval of WAVE communication was changed to 2 s owing to the short time spent in the experiment while extracting location information and entering the track on the graph. Moreover, the location information data renewed using AIS communication was duplicated to compare and analyze WAVE and AIS communications.

For ship A, the first location information was received at 12:08:01 on the graph. Subsequently, information was received at approximately 30 s, including 29, 31, 29, and 31 s. For ship B, the first location information was received at 12:07:04. Subsequently, information was received at approximately 30 s,

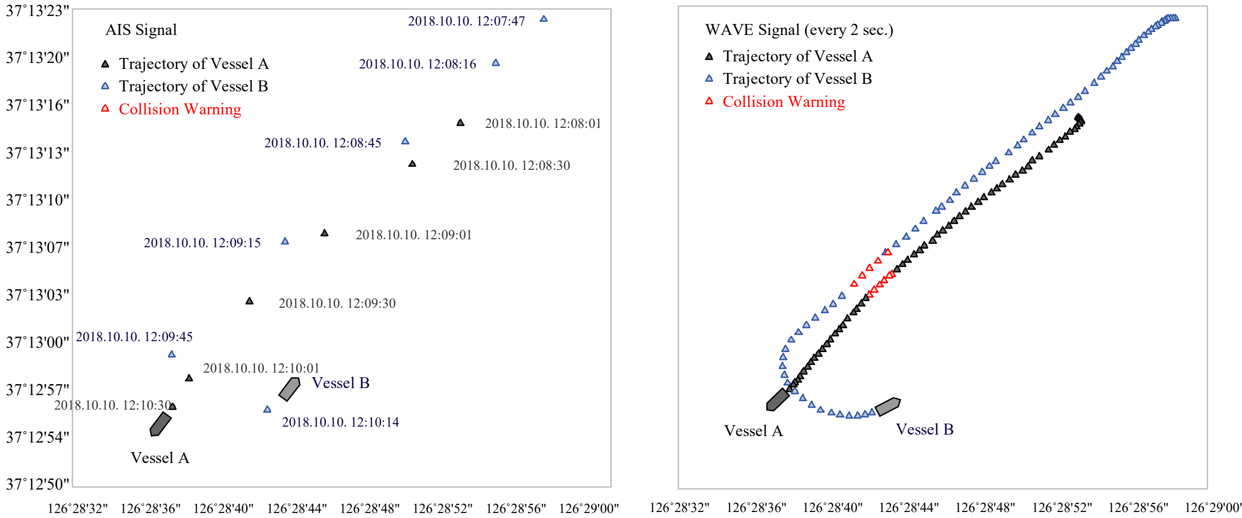

Fig. 17. Ship track of experiments based on real ship: scenario (b)

including 29, 29, 30, 30, and 29 s. In this experiment, two ships sailed in parallel in such a manner that ship B overtook ship A and then started to quickly turn at an angle of 90° while ship A continued to travel forward. However, there was no collision through AIS during the experiment.

As shown in the experiment in Fig. 17, a situation in which two ships first sail in parallel, followed by one ship rapidly overtaking the other ship, followed by a sudden veering can always occur with small ships. In cases of collision in imminent situations, the collision avoidance system for small ships using AIS communication did not perform appropriate actions to avoid collision because of limitations in communication characteristics such as the AIS communication interval.

4. Implications

While the collision avoidance system based on WAVE communication alerted the navigator of the full risk of collision, this alarm was not raised or transmitted in the collision avoidance system based on AIS communication. In the proposed system based on WAVE communication for small ships, information including the location of a ship was renewed every 0.1 s. Consequently, the system alerted the navigator of a risk of collision based on sudden veering or route change at a short distance to allow the navigator to perform the appropriate collision avoidance action to avoid the collision.

As shown above, the collision avoidance system based on WAVE communication was found to be effective for small ships. In addition, the existing AIS system was found to be an unsuitable communication system for autonomous ship navigation. In a case of a lack of control in the stage what a system is controlling ships, this can cause serious marine accidents such as collisions. Consequently, the collision avoidance system developed in this study is appropriate for autonomous small ship navigation. In addition, we anticipate that the results of this study will provide references to establish a ship–ship communication for autonomous small ship navigation while continuously tracking ships despite the absence of location information or control.

V. CONCLUSIONS

In this study, a collision avoidance system was developed based on WAVE communication technology for autonomous small ship navigation. The proposed system comprised receiving, computing, collision risk determination, and display sections, and experiments were conducted on real ships to evaluate the appropriateness of this system. According to the experiment conducted on real ships, our collision avoidance system based WAVE communication showed a short interval of information transmission with high reliability of data. Consequently, it was found to be effective as a collision avoidance system for small ships, such as fishing boats, which rapidly change direction and speed. In addition, it was found to be appropriate for autonomous ship navigation when the system is controlling a ship.

The proposed system is a customized collision alert system for autonomous small ship navigation. However, the following limitations exist. First, the experiments were conducted with crewmembers on board, corresponding to levels 1 and 2 of autonomy proposed by IMO. To validate the effectiveness of the system at the higher level of autonomy, namely levels 3 and 4, an experiment should be performed on an unmanned ship. Jung et al. (2018) and Nam et al. (2019) conducted an experiment on an actual unmanned surface vehicle to solve the efficiency problem of remotely operated vehicle's battery and underwater robot control. Second, it is necessary to develop an exclusive collision avoidance algorithm for small ships. Lee at al. (2019) analyzed that in the case of small ships, it is difficult to maintain the route owing to the severe movement of the bow direction based on external forces, and an error may occur in determining the risk of collision when deviation from the original route occurs frequently. Third, it is necessary to standardize autonomous navigation technology. It would be unwise to directly apply existing WAVE communication technology to marine transportation without sufficient verification. Further, for developed technologies to be interlinked and compatible with existing technology, technical standards must be defined first.

Therefore, in future studies, it is necessary to investigate and develop a collision avoidance algorithm for autonomous small ships from various angles by considering the steering and operational characteristics of small ships. Although communication technology, monitoring, and alarm function for small ships are important, the reliability and accuracy of information are determined according to algorithms. Moreover, it becomes necessary to optimally improve and develop the communication technology in a marine environment through sufficient research, development, and experiment. In terms of application service, it is necessary to use available WAVE communication technology for transmission of highly reliable information with secure communication while pursuing the development of various services and continuously researching the standardization of technology appropriate for sea.

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