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Effect of Ship Motion Prediction Model on Navigational Safety

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In this study, the effect of the motion prediction model (MPM), which is a ship behavior prediction model that predicts and provides short-term motion by analyzing ship location information and motion characteristics in real time, on navigational safety was studied. The electronic chart system (ECS) was installed with the MPM on a ship to connect with sensors such as those of the global positioning system (GPS), automatic identification system (AIS) plug, and real-time kinematic (RTK) for logging the real-time location and dynamic information. The MPM predicts the future motion and position of a ship by calculating the logging data, and it was verified that the motion of the ship predicted by the MPM and the actual navigation were very similar. In this study, the nondimensionalized length over all (LOA) was analyzed and found to have an average of 0.0713, confirming that the value predicted by motioning an actual operation was very accurate. In addition, as a result of the user satisfaction survey of the MPM, the adjective rating scale defined by the system usability scale was evaluated to be good, which was verified as convenient to use. In the case of the effectiveness analysis of the MPM by an expert group, it was found that 56.17% of the maritime accident factors alleviated the risk by 80% and that 20.8% of the factors alleviated the risk by 100%. Through this study, it was found that the result of analyzing the movement of individual ships and predicting their motion is an important impact factor for preventing ship collisions. In the future, the MPM is expected to enhance the operational safety of ships operated by self-pilotage, such as cargo ferries and passenger ships, which are less regulated by governments.

1. Introduction

1.1 Research background

The International Maritime Organization (IMO) enforced the use of the electronic chart display and information system (ECDIS) in 2012. The ECDIS displays the position of the ship and electronic charts in real time on the monitor screen of the ship navigation support system, and it can replace the analog method of planning the routes and operation of ships using paper charts. Currently, the ECDIS is compulsory for all vessels over 500 tons. However, despite

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worldwide efforts, the rate of maritime accidents due to human error is 82%, and that caused by coastal vessels and fishing boats is 72%. Despite the development of technology and industry, accidents still occur in the sea.

Table 1 shows the 2021 statistical data of ship accidents disclosed by the Korean Maritime Safety Tribunal (KMST). It can be seen that the number of maritime accidents has steadily increased by about 7.5% every year for the past five years. Despite the spread of the latest project and marine safety systems such as Monalisa, EfficienSea, ECDIS, and ECS, it is judged that these types of ship support equipment do not perfectly protect the navigator and the actual site. In addition, the data show that the accident rates of passenger ships, fishing boats, and tugboats that are subject to neither compulsory ECDIS nor mandatory pilotage are rather high. In particular, passenger ships and cargo car ferries are vulnerable to accidents because they require frequent arrival, departure, and berthing.

Figure 1 shows the statistical results of maritime accidents classified by factor. Physical accidents such as contact and collision account for a high percentage of human-caused accidents, excluding mechanical causes such as propeller winding and engine damage.

Table 1
Number of maritime accidents (2016–2020).[1]

Year	Number of accidents		Number of ships involved in accidents		Human injuries	
	Fishery	Others	Fishery	Others	Fishery	Others
2016	1646	661	1794	755	324	87
2017	1778	804	1939	943	352	171
2018	1846	825	2013	955	303	152
2019	1951	1020	2134	1140	450	97
2020	2100	1056	2331	1204	451	102
SUM	9321	4366	10211	4997	1880	609

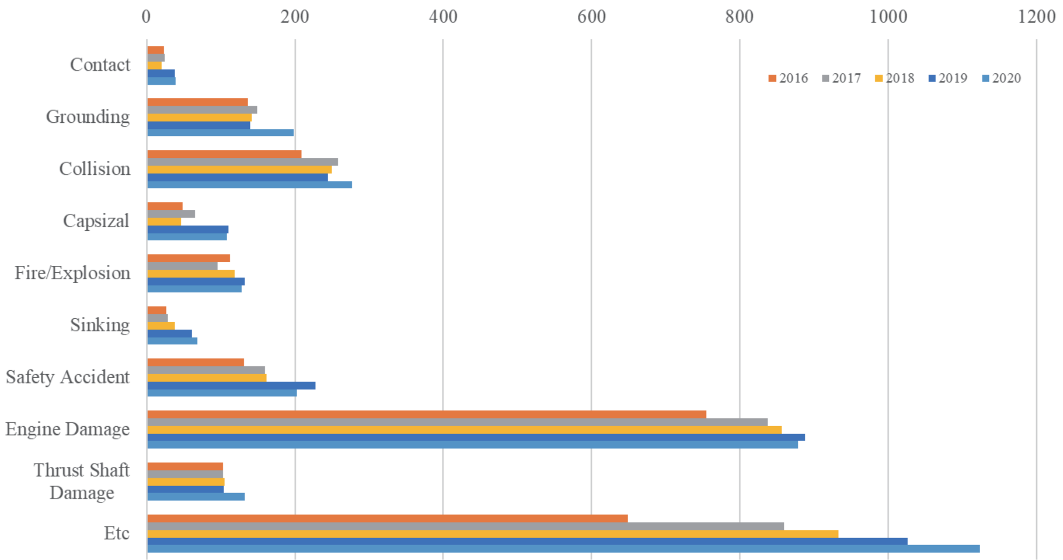

Fig. 1. (Color online) Causes of ship accidents in Korean seas (2016–2020).

1.2 Preliminary research

Yang defined a model for classifying ship collision risk information using logistic regression for a total of 56 types of encounter such as overtaking, crossing, head-on collision, other with low collision risk, and safe.(2) In addition, Le *et al.* conducted a ship behavior prediction study using a Kalman filter to prevent collision between leisure ships and fishing boats.(3) They intended to develop a system that estimates the speed and distance between a ship and another party, applies a Kalman filter to the signal measured using a laser sensor, and avoids the risk of collision. However, a laser sensor was developed in the actual phase of research to measure the signals.

Roh predicted the roll, pitch, and heave values of hull motion by applying the long short term memory (LSTM) deep learning technique to time series data and compared them with actual data.(4) As a result, simulations were performed for 75 damage areas in the hull, three damage degrees, three sea conditions, and eight angles of incidence. The actual measured ship's motion results and predicted values were similar.

Park *et al.* developed a model for measuring the risk of shipbuilding burden in the port using the survey data of ship operators.(5) By applying this model to small fishing boats, the risk was found to be stably evaluated and that the accuracy and alarm interval were also suitable from the user's viewpoint.

You verified the behavior of a ship that lost its resilience through experiments and confirmed that, unlike the lateral slope caused by the natural external force (e.g., wind and wave) during operation, the lateral slope caused by the negative resilience was a considerable risk to ship operation.(6) Christian and Douglas studied the mobility of a ship's outer deck to reduce the risk of landing fixed-wing aircraft on an aircraft carrier at sea.(7) As a result, the motion information on the ship's vertical and horizontal movements was calculated in detail, and the location information of the deck was predicted to help the aircraft land.

Hoong and Ashim proposed a four-stage collision risk system to develop a collision risk model between ships in a port.(8) They found that the risk level increases with the size of the ship and that safety guidelines higher than the average are required because it is difficult to secure watches when operating at night. Choi studied the impact of motion prediction on ship navigational safety, and it was found that predicting the future position would reduce the number of ship accidents in the ocean.(9)

Zhang and Liu conducted a study to predict the heading angle of a ship using the wavelet neural network (WNN), a wavelet artificial neural network.(10) By applying the Extended Kalman Filter (EKF) to the real-time AIS data of ships, Fossen and Fossen predicted the ship position between 1 and 180 s.(11) However, it was judged that it was difficult to use in real time because the information cycle of AIS was very long.

Lisowski calculated the risk to determine the optimal avoidance path in a dangerous situation where collision between ships is expected and presented a low-risk avoidance path for each case.(12)

Ann *et al.* designed a development strategy of a ship motion prediction system for the portable pilot unit (PPU).(13) The ability of the pilot is important when berthing the ship, but now this ability relies on know-how and technology, and only expensive PPU equipment is sold in the field. Ann *et al.*'s paper was used as a basis of this study on designing a general-purpose PPU concept that predicts future locations using ship location, speed, and heading (HDG).

The analyses of the safety and motion prediction of ships have mostly been studied using simulation-based prediction and risk warning models. Research on evaluating safety in real time and predicting location or heading during operation by installing precise location information sensors such as those of the global positioning system (GPS) and real-time kinematic (RTK) on ships is insufficient.

Until now, in the field of marine safety and disaster response, safety models to prevent accidents and the verification of various cases through simulation have been important. In addition, it is judged that deciding where the ship will go and in which direction it should head is the unique task of the captain and pilot, and it is judged that not much research has been conducted in general fields.

2. Research Methods

In this study, the effect of the motion prediction model (MPM), which is a ship behavior prediction model that predicts and provides short-term motion by analyzing ship location information and motion characteristics in real time, on navigational safety was studied.

The MPM predicts the motion of ships developed previously through the SMART Navigation Project in Korea. The MPM consists of a kinematic algorithm and dynamic types such as the EKF and DEKF algorithms. According to the preliminary research of Yang *et al.*, the kinematic algorithm predicts the future ship behavior by analyzing the past ship behavior and the dynamic algorithm also predicts the ship behavior using Kalman filters and past ship behavior and ship control data such as steering and engines.[14] Table 2 shows the detailed concept and process of the MPM algorithms.

Table 2
Overview of MPM kinematic and dynamic algorithms.

	Kinematic	Dynamic (EKF, DEKF)
Method	Analyzing historical kinematic data over a period of time from the present, predicting future ship behavior by the extrapolation method	Establish a ship dynamics model, determine the motion characteristics of a ship by the parameter estimation method using past ship kinematics, control, and external environment data, and predict future ship behavior by the simulation method
Advantage	• Use historical data for a short period • No need of control data from the vessel • Numerical analysis calculation time is short	• Fast and accurate predictions • Filtering with state variable • Reflects the external environment such as water depth, wind, and current
Remarks	Filtering for state variable is difficult owing to the nature of extrapolation, and noise of input data can cause large errors	• Historical data over a sufficiently long period for parameter estimation of motor characteristics are required • Suitability of dynamic model considering ship characteristics is required

2.1 Verification of MPM between simulation and sea trial

First, the error between the predicted value and the actual measured value was analyzed to verify the accuracy of the MPM. The accuracy was analyzed by comparing the predicted trajectory of the ship determined using the kinematic algorithm used in the MPM and the EKF and DEKF algorithms with the actual navigation trajectory. In addition, the MPM was verified using a ship steering simulator that replicated the actual ship exactly. In the simulation, a 100-m-scale test ship was used, and in the sea trial, various passenger ships traveling to various islands in Korea were examined to reflect the actual marine environment.

Table 3 shows simulation test cases of this research based on the standards for ship maneuverability developed by the IMO. The speed of the vessel was set to 8 and 20 knots, and the normal wind and signal conditions and the storm warning (wind speed: 14 m/s, and wave height: 3 m) were classified. In addition, the rudder angles of the ship were set to starboard at 5, 15, and 30 degrees. The ship length was 104.7 m and the width was 15.0 m.

Table 4 shows test cases designed to verify the MPM using ships operating on the coast of Korea. Daewon and Gaja sum are ferry ships that operate among islands with travel times of 1–2 h over relatively short distances. Silver Cloud and Queen Mary are mid- to long-distance passenger ships that travel for more than 6 h.

Table 3
Test cases of simulation.

Test case	Rudder angle	Speed (knots)	External force
ST 1	Starboard 5°	8.0	Wind: 0 m/s Wave: 0 m
ST 2	Starboard 15°		
ST 3	Starboard 30°		
ST 4	Starboard 5°	20.0	
ST 5	Starboard 15°		
ST 6	Starboard 30°		
ST 7	Starboard 5°	8.0	Wind: 14 m/s Wave: 3 m
ST 8	Starboard 15°		
ST 9	Starboard 30°		
ST 10	Starboard 5°	20.0	
ST 11	Starboard 15°		
ST 12	Starboard 30°		

Table 4
Test cases of sea trial.

Test case	Type	Specifications	Course
FT 1 (Daewon)	Car ferry	59.2 × 11.6 m^2; 322 tons	Gyeokpo–Wedo
FT 2 (Silver Cloud)	Car ferry (Roro)	160 × 24.8 m^2; 20263 tons	Wando–Jeju
FT 3 (Queen Mary)	Car ferry (Roro)	192 × 27 m^2; 30343 tons	Jeju–Mokpo
FT 4 (Gaja Sum)	Car ferry	55.7 × 13 m^2; 496 tons	Wando–Jeju
FT 5 (Silver Cloud)	Car ferry (Roro)	160 × 24.8 m^2; 20263 tons	Jeju–Wando

2.2 System usability scale to MPM validation

The user satisfaction survey of the MPM was evaluated on the basis of the SUS-based Likert 5-point scale to calculate the satisfaction score and adjective rating. The SUS method used in this study was developed by John Brookie in 1986 and is a methodology suitable for practical evaluation regardless of the service platform.(15,16) Since its development, SUS has been used in various ways in the industry for over 30 years and has been verified from various angles.

After the user satisfaction survey, an expert group, for example, navigators, analyzed the correlation between the main causes of international maritime accidents and the MPM, and quantitatively analyzed the resolution rate of the main causes of maritime accidents when the ship behavior prediction information predicted by the MPM was provided.

2.3 Expert evaluation of MPM concerning navigational safety

According to related preliminary research, such as that by Kim *et al.*, to find the fundamental cause of marine accidents in the recent marine field, marine accident data analysis is prioritized.(17) This includes not only ship operation information, but also overall information of accident situation, such as weather conditions at the time and the characteristics of nearby ships. The purpose of marine accident data analysis is to identify the root cause of the accident and prepare measures to prevent the recurrence of marine accidents. Lee and Park investigated marine accidents caused by pilot error and derived the key words for the accidents using text mining techniques.(18) In addition, marine accidents were classified and analyzed into two or more causes by applying them to the SHEL model.

After the primary marine accident data analysis is completed, the causes, causal relationships, and influencing factors are quantitatively analyzed in accordance with the category of marine accidents defined by international organizations. For the cause category of marine accidents, the Code for the Investigation of Marine Casualties and Incidents developed by IMO is the most representative reference. In this study, 90 factors related to the MPM were identified by analyzing the IMO International Marine Accident Investigation Code, the Australian Transportation Safety Bureau, KMST, and the Maritime Police Agency's classification of marine accident causes.

In addition, each factor was classified into five types: human factor for each navigator, ship factor, shipping factor, natural environmental factor, and human and physical external factor to confirm whether the effect of the MPM differs depending on the characteristics of the factor. The accident cause category used as a reference classifies the cause of the accident into various categories, but in this study, the human errors caused by the person operating or managing the ship and natural environmental factors that cannot be controlled were considered important, so it was classified into two categories in the first step. On the basis of the references, it was classified into five categories.

Expert evaluation was conducted by 36 experts who had a marine engineer's license and were able to operate ships at home and abroad. They evaluated how the MPM would help solve the situation or problems specified in each question if it were to be provided to ship operators in real time.

3. Results

Figure 2 shows a ship navigation equipment screen when verifying the MPM through a sea trial near Jeju Port. The solid black line in the center shows the tracking of the ship's voyage, and the black rectangle indicates the ship. There are six red forms in front of the ship, which are the predicted future positions of the ship every 10 s. The navigator operates the vessel and is provided with a position from 10 to 60 s in real time. Safe ship operation is possible because the movement of the ship can be expected in the process of porting the ship. Yang and Oh showed that monitoring the real-time operation information of ships can prevent the possibility of marine accidents in advance.(19) In addition, because of the effect of supporting on-board decision-making for the safe operation of ships, the MPM's prediction of ship location information for navigators is considered to contribute to creating a safe sea.

Through the simulation and sea trial, it was verified that the ship location information predicted by the MPM was accurate. In some cases, the MPM was affected by the size of the ship and natural environment factors, but the prediction accuracy was high as a result of the nondimensionalized LOA of the ship and deviation.

In the user satisfaction evaluation, it was evaluated as having a Good grade, and it was induced that the system to which the MPM was applied was convenient for navigators to use. In the expert evaluation of the marine field, many of the 90 major accident risk factors were found to be resolved by the MPM.

3.1 Verification of MPM between simulation and sea trial

In the simulation, we compared the kinematic, EKF, and DEKF algorithms used by the MPM that predicts ship behavior. Since the equation and filter used for each algorithm were different,

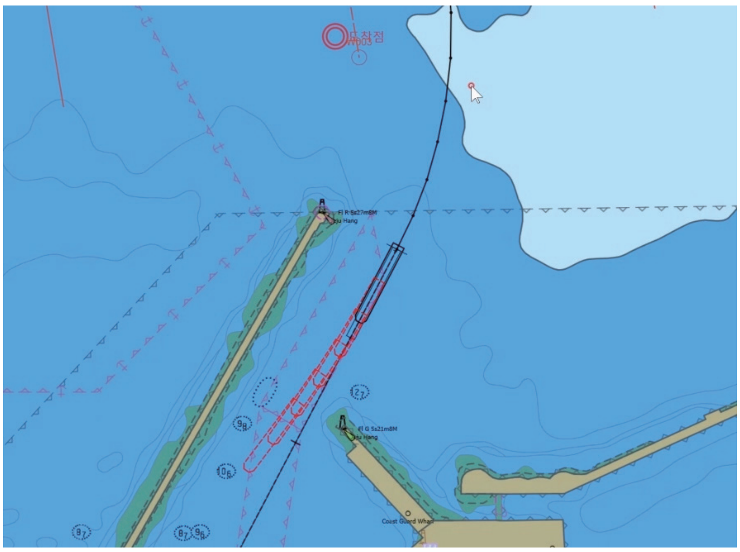

Fig. 2. (Color online) Sea trial with MPM near Jeju Port.

there were slight differences in predicted location information and heading. Table 5 shows the results of verifying the MPM through simulation under the conditions in Table 3 in Sect. 2.1 of this paper. As a result, it was confirmed that the motion of the ship predicted by the MPM and the actual navigation were very similar. In the test case, it was also partially confirmed that the higher the speed and rudder angle of the ship, the greater the error between the predicted value and the actual position.

In the sea, when calculating location information or distance, it is expressed as a nondimensionalized LOA of the ship. Unlike land vehicles, a ship is long and the operating route range is very long, so nondimensionalized deviation or errors are used for safety check. The nondimensionalized LOA is actively used because the risk is calculated by assuming exercise conditions that enable evacuation or stopping in consideration of the length of the ship. The simulation tests of the cases in Table 4 show the value of the nondimensionalized LOA to be 0.0734.

Table 6 shows the logs for the five test cases, where GPS, AIS plug, and RTK sensors are installed on the actual and passenger ships operated from the origin to the destination. The MPM predicted the future position in real time using the ship's speed and HDG, course over

Table 5
Results of verifying Verification MPM through simulation.

Test case	Mean deviation (m, L/LOA)		
	Kinematic	EKF	DEKF
ST 1	0.566 m (0.005)	0.533 m (0.005)	1.319 m (0.011)
ST 2	1.044 m (0.019)	0.988 m (0.019)	1.365 m (0.026)
ST 3	1.521 m (0.028)	1.398 m (0.026)	0.970 m (0.018)
ST 4	5.085 m (0.091)	4.927 m (0.091)	5.924 m (0.109)
ST 5	8.075 m (0.139)	7.831 m (0.139)	7.998 m (0.143)
ST 6	9.021 m (0.158)	8.646 m (0.156)	8.608 m (0.155)
ST 7	0.305 m (0.006)	0.359 m (0.007)	0.633 m (0.012)
ST 8	1.583 m (0.029)	1.506 m (0.028)	1.433 m (0.027)
ST 9	1.909 m (0.035)	1.837 m (0.034)	1.683 m (0.032)
ST 10	5.09 m (0.091)	4.913 m (0.091)	6.336 m (0.117)
ST 11	8.184 m (0.145)	7.948 m (0.146)	7.318 m (0.134)
ST 12	9.16 m (0.159)	9.055 m (0.158)	3.096 m (0.054)

Table 6
Results of verifying MPM in sea trial.

Test case	Prediction time (s)	Mean deviation (m)	Mean deviation L/LOA
FT 1	10	3.5	0.06
	30	9.9	0.17
FT 2	10	2.1	0.01
	30	6.5	0.04
FT 3	10	6.6	0.03
	30	9.5	0.05
FT 4	10	3.3	0.06
	30	6.3	0.11
FT 5	10	6.6	0.04
	30	11.0	0.07

ground, speed over ground, and rate of turn logs. The units were 10 and 30 s later.

Since the HDG of the ship changes immediately in accordance with the steering operation of the operator, it was found that the 10-s-later prediction value of the location and direction of the ship that we boarded was much more accurate. In addition, the nondimensionalized LOA of the sea trial was 0.0640. As a result of the comparison of the MPM algorithms between kinematic and EKF, no significant difference in deviation for the position was found. However, the deviation for the heading tended to increase slightly in DEKF. The increase in deviation in DEKF is expected given that the dual extended Kalman filter used in the algorithm is unsuitable for use in MPMs. Considering the scale of the ship and the characteristics of the ship's wide area and route, the three MPM algorithms are considered to yield relatively accurate predictions of ship behavior for positions after 10 and 30 s.

In this study, the nondimensionalized LOA was analyzed to have an average of 0.0713, confirming that the value predicted by the MPM during actual operation was very accurate. In addition, the nondimensionalized LOA of the sea trial was 0.0713. The nondimensionalized LOA of the simulation was 0.0734, as the simulation includes six cases of conditions corresponding to a wind speed of 14 m/s and a wave height of 3 m; hence, the accuracy of the predicted value is judged to be low. In the case of sea trials, it can be seen that the prediction accuracy is high because the ship actually operates for several hours and requires less steering in areas outside the port. Among the sailing conditions affected by waves and winds, a heading error of less than 2 degrees on average is not expected to have much effect on the actual ship sailing situation.

3.2 System usability scale to MPM validation

As a result of the user satisfaction evaluation of this MPM designed on the basis of a Likert 5-point scale, it can be seen that user satisfaction is as high as a Good grade. Fifty-one people participated in the user satisfaction evaluation, including researchers, managers, and ship operators in the maritime field.

3.3 Expert evaluation of MPM concerning navigational safety

Figure 3 shows a simulation result in which a ship enters DangJin Port in PyeongTaek and is intended to help an expert understand the MPM. As the ship enters DangJin Port in PyeongTaek, it requires more steering than in the open sea: the ship's location after 10 and 30 s is immediately shown on the ECDIS screen. Previously, ship docking at the port was based on the pilot's know-how and intuition, but the MPM was evaluated as being very convenient for acquiring information because it provides real-time prediction information based on sensor information. Unlike on land, the sea has a fluid characteristic, making it difficult to immediately judge the movement of ships, and the information provided by the MPM was evaluated as very important in preventing collision with port structures.

In the results of the effectiveness analysis of the MPM by the expert group, it was found that among the 90 factors, an average of 56.17% of the factors resolved the risk by 80% and 20.80% of the factors resolved the risk by 100%. This is judged to indicate a high positive correlation of

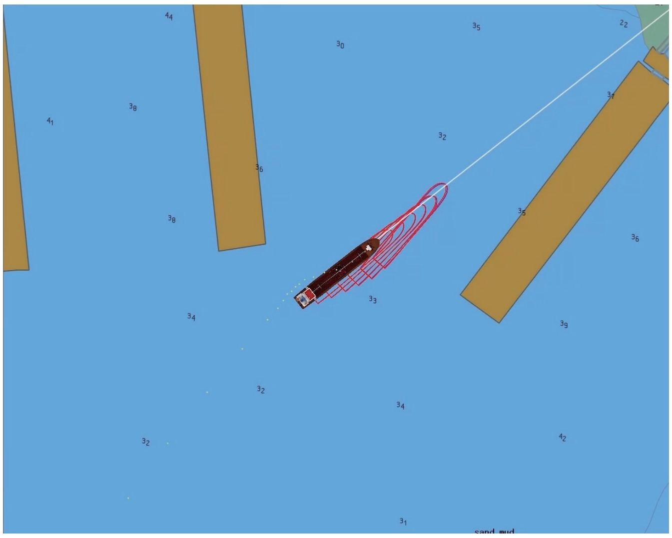

Fig. 3. (Color online) Result of simulation with MPM near DangJin Port.

the MPM with the identification of the direct cause of marine accidents, and it can be considered that accident reduction is expected.

There were significant differences in response results for each type of factor, and in the case of items with strong correlation, natural factors and human and physical factors were evaluated more than 10% higher than other factors. The MPM is considered to be helpful in the above cases because if the ship need not be boarded, the operator's experience, know-how, and immediate response must be used.

It was found that the MPM is more helpful in an environment for which factors are difficult to control and manage compared with general factors (e.g., individual human factors and ship factors) that ship operators can control or solve using their know-how or knowledge.

3.4 Overall results of research

In this research, we found that the result of analyzing the movement of individual ships and predicting the motion considering the fluid flow, which is characteristic of the sea, is an important impact factor in preventing ship collisions. Since the MPM provides short-term forecast information of around 10 and 30 s ahead, it can be seen that it is a suitable model for situations where an immediate response by the navigator is required, such as the situation where a ship is berthing in a port.

In addition, the deviation evaluated by the algorithm was insignificant. The behavior of ships 10 and 30 s ahead was predicted using the kinematic, EKF, and DEKF algorithms, and the position error from the actual trajectory was insignificant. Since each algorithm is calculated using the ship's location and motion information, the resulting values are judged to be similar. As a result of verification in the actual sea, it was found that the prediction accuracy was high in the same way as the verification of the ship control simulator. In particular, speed was identified as a major factor at 20 knots and above, although steering was a considerable factor below 10 knots.

4. Conclusions

In this study, we verified in various ways through experiments and human evaluations whether the MPM developed in past projects helps the safe operation of ships. The target situation of using the MPM was defined as self-pilotage without a pilot or ECDIS, making it different from previous studies. Instead of international and large ships (e.g., LNG ships, cargo ships, and container ships), the MPM is suitable for coastal passenger ships, road ships, and cargo ferries of 100 to 400 tons as such ships would proceed by self-pilotage to nearby ports.

Real-time ship behavior prediction, such as crossing between ships in congested areas or narrow waterways, is expected to play an important role in safety management and accident reduction, as well as in the operation of ships by self-pilotage in ports. As Sunaryo *et al.* defined the risk control option in terms of IMO's Formal Safe Assessment, the MPM could be a maritime risk control option that enables prevention and control before accident risk factors (hazards) lead to accidents (risk).[20]

Two additional studies are required to complete the MPM and its utilization in ships. First, since the MPM predicts the ship's position every second, the predicted value tends to change whenever the navigator adjusts the steering when the ship is docking in port. It is necessary to provide more stable prediction results by adjusting the prediction sensitivity of the MPM by reflecting the ship's operation mode or location information. Second, additional research is needed so that the algorithm used in the MPM changes the prediction result in accordance with the size, weight, and type of operation in consideration of the type and specifications of the ship. The current model yields predictions on the basis of ship motion information, so the unique characteristics of each ship cannot be reflected, such as towage situation with tug boats.

Passenger ships that are not subject to the compulsory boarding of pilots and ECDIS operation or cargo ferries operating in island areas are managed on the basis of the ship operator's know-how and intuition. In the future, when navigational supporting systems with the MPM are installed in ships, it is expected that the operational safety of self-pilotage ships will be enhanced.

Acknowledgments

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