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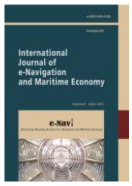

Original article

A Fuzzy-based Rough Weather Navigation Decision Support System Using an Enhanced RRW Algorithm

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Abstract

Recent advances in Maritime Autonomous Surface Ships (MASS) and e-Navigation technologies have increased the demand for decision support systems based on real-time maritime environmental information. In rough weather conditions, navigators are required to comprehensively assess wave conditions, atmospheric pressure, and wind variations. However, such decisions are still highly dependent on the experience and judgment of individual navigators. Therefore, quantitative decision support techniques are required for autonomous and remotely operated ships.

This study proposes a rough weather navigation decision support system based on real-time wave observation data. The proposed system utilizes an X-band radar-based wave observation system to estimate significant wave height and employs a fuzzy inference engine with atmospheric pressure information to calculate heavy weather risk. In addition, a ship-tonnage compensation module is introduced to reflect the different impacts of rough weather according to vessel size. The calculated risk is used as an input to the Enhanced Recommend System under Rough Weather (RRW) algorithm. Based on the relative position of the vessel to a typhoon, the system recommends either Heave-to maneuvering in the dangerous semicircle or Scudding maneuvering in the navigable semicircle.

Simulation results show that the proposed system appropriately estimates heavy weather risk according to wave height and atmospheric pressure conditions. Furthermore, the Enhanced RRW algorithm is activated only when the estimated risk exceeds a predefined threshold, thereby reducing unnecessary maneuvering actions. The proposed system can support safe navigation of conventional merchant ships and is expected to be applicable to decision support systems for MASS and remote ship operation environments.

Keywords: Heavy Weather Navigation, Wave Observation System, Fuzzy Inference, RRW, Navigation Decision Support, Maritime Autonomous Surface Ship (MASS)

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1. Introduction

Recent advances in Maritime Autonomous Surface Ships (MASS) and smart navigation systems have led to increasing research efforts aimed at recognizing the surrounding marine environment in real time and supporting navigational decision-making based on such information. The International Maritime Organization (IMO) defines MASS as ships that can operate with varying degrees of autonomy without direct human intervention. As the adoption of MASS continues to expand, the importance of situation awareness and decision support technologies capable of replacing or assisting the experiential judgment of navigators has significantly increased (IMO, 2021). Furthermore, through its e-Navigation strategy, IMO has emphasized the need for integrated information management and decision support frameworks that combine shipboard and shore-based maritime information to enhance navigational safety and operational efficiency (IMO, 2008; IMO, 2018).

In actual heavy weather navigation, navigators determine appropriate maneuvering actions, such as Heave-to and Scudding, based on their experience and expertise by comprehensively assessing changes in wind direction, atmospheric pressure, and sea conditions. In addition, navigational decisions under rough weather conditions must consider various hazards, including slamming and broaching (Yeom, 2020; Yoon, 2022). However, such decisions are highly dependent on individual experience and judgment. Therefore, quantitative decision support technologies are required, particularly for autonomous and remotely operated ships, where experienced human intervention may be limited (Porathe et al., 2014; Kim et al., 2019).

Previous studies on ocean wave observation have primarily focused on estimating wave parameters, including wave height, wave direction, wave period, and wavelength using X-band marine radar systems. In general, radar images are processed using Fast Fourier Transform (FFT)-based signal analysis techniques, and the estimated wave information is validated against measurements obtained from oceanographic buoys (Nieto-Borge et al., 2000). However, most previous studies have focused on the observation and estimation of wave information itself, while relatively few studies have utilized observed wave information to support navigational decision-making under rough weather conditions (Ro et al., 2023).

Moreover, existing weather routing studies have mainly focused on fuel-efficient route optimization and voyage planning over ocean passages (Fabbri et al., 2019; Szlapczynska, 2015). Although these studies provide valuable guidance for long-term route optimization, they are less suitable for supporting immediate maneuvering decisions under rapidly changing local sea conditions. In particular, studies directly linking real-time radar-based wave observation data with heavy weather maneuvering strategies for risk assessment and maneuver recommendation remain limited (Ro et al., 2023). While conventional weather routing techniques are primarily designed for long-term route optimization over several hours or days, actual heavy weather navigation requires short-term maneuvering decisions capable of responding to rapidly changing environmental conditions.

The increasing deployment of autonomous ships further highlights the importance of this issue. Unlike conventional vessels, autonomous ships cannot directly rely on the experiential judgment of navigators. Consequently, technologies capable of recognizing marine environmental conditions, evaluating navigational risks, and supporting appropriate decision-making based on real-time sensor data are becoming essential. Furthermore, decision support systems are also needed for conventional ships to enhance navigators' situation awareness and support safe navigation under heavy weather conditions.

Therefore, this study proposes a navigation decision support system for heavy weather operations based on real-time wave observation data. The proposed system collects marine environmental information in real time using a wave radar, barometer, anemometer, GPS receiver, and clinometer. A fuzzy inference-based risk assessment algorithm is employed to estimate the level of heavy weather risk. In addition, a navigation decision support algorithm is developed to recommend appropriate maneuvering methods based on the estimated risk level and the vessel's relative position to a typhoon. The calculated risk level and maneuvering recommendations are provided to support decision-making for both navigators and remote ship operation systems.

2. Heavy Weather Maneuvering Analysis

When a vessel encounters rough weather, heavy weather avoidance maneuvers based on Dove's Law are commonly employed. Rough weather can be defined as a sea condition accompanied by strong winds and high waves, and wave height is generally considered one of the primary criteria for determining its severity. Internationally, sea conditions are classified into ten levels, ranging from 0 to 9, according to the Sea State Code established by the World Meteorological Organization (WMO) (KMA, 2026; NOAA, 2026). However, even under identical wave height conditions, the impact on a vessel may vary depending on factors such as vessel size, displacement, and stability characteristics. Consequently, the assessment of rough weather conditions and the corresponding maneuvering decisions still rely heavily on the experience and judgment of the ship's master.

Table 1: WMO sea state classification according to wave

height.

Grade 1	**0 ~ 0.1m**
Grade 2	0.1 ~ 0.5m
Grade 3	0.5 ~ 1.25m
Grade 4	1.25 ~ 2.5m
Grade 5	2.5 ~ 4m
Grade 6	4 ~ 6m
Grade 7	6 ~ 9m
Grade 8	9 ~ 14m
Grade 9	At least 14m

When a vessel enters severe rough weather conditions, such as a typhoon-affected area, wave heights generally increase significantly along with wind speed. Under such conditions, the maneuvering performance of a vessel may deteriorate considerably, and improper maneuvering can result in serious accidents, including structural damage, cargo damage, slamming, broaching, capsizing, and even sinking. In particular, accidents occurring in rough weather often develop rapidly within a short period of time. Therefore, it is essential to continuously monitor meteorological conditions and the operational status of ship maneuvering equipment before and during heavy weather navigation.

The two representative maneuvering methods used in rough weather conditions are Heave-to and Scudding. Heave-to is a maneuvering technique in which the vessel maintains its bow toward the wind and waves while proceeding at the minimum speed required to retain steering control. In the Northern Hemisphere, when a vessel is located on the right side of a typhoon's direction of movement, it is considered to be within the Dangerous Semicircle. In this case, the wind direction typically shifts clockwise. Since the vessel is more likely to be drawn toward the typhoon center, the recommended maneuver is to keep the wind on the starboard bow and proceed away from the storm center. This maneuvering principle is associated with the well-known 3R Rule derived from Dove's Law. According to Dove's Law, the 3R (Right-Right-Right) Rule indicates that when the wind direction shifts to the Right, the vessel is located in the Right semicircle, and the wind should be kept on the Right bow while maneuvering away from the storm center. Conversely, the LLS (Left-Left-Starboard Stern) Rule indicates that when the wind shifts to the Left, the vessel is located in the Left semicircle, and the vessel should proceed with the wind on the Left quarter (stern quarter) while moving away from the storm center.

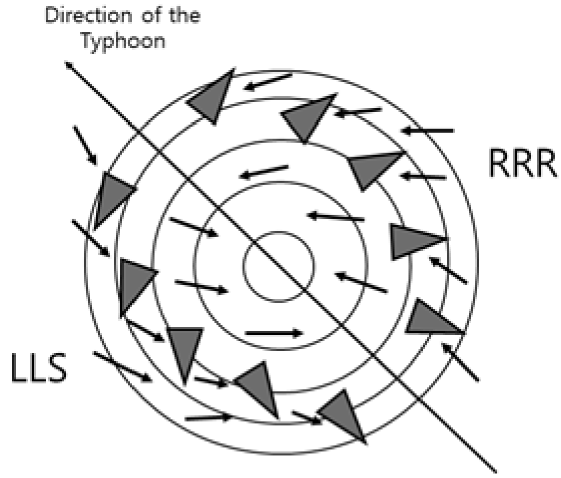

Figure 1: Heavy weather maneuvering concept based on Dove's law

In contrast, Scudding is a maneuvering method in which the vessel runs before the sea while receiving waves from the quarter astern. In the Northern Hemisphere, when a vessel is located on the left side of the typhoon track, it is considered to be within the Navigable Semicircle, where the wind direction generally shifts counterclockwise. Under these conditions, the vessel naturally moves away from the typhoon center. Therefore, it is recommended to keep the wind on the port quarter and proceed away from the storm center. This maneuvering principle is associated with the LLS Rule of Dove's Law (Yoon, 2022; Seol, 2015).

Since the direction of typhoon rotation is opposite in the Northern and Southern Hemispheres, determining whether the vessel is located in the Northern or Southern Hemisphere is an essential prerequisite for applying appropriate heavy weather maneuvering strategies. Consequently, a decision support system for rough weather navigation requires not only wave information but also various environmental and ship-motion data that can be analyzed comprehensively.

To determine whether a vessel is approaching or moving away from the center of a storm, atmospheric pressure information obtained from a barometer is required. In addition, an anemometer and Anemoscope are necessary to analyze changes in wind speed and wind direction. Furthermore, GNSS (Global Navigation Satellite System) position information is essential for determining the vessel's geographical location and hemisphere. Therefore, safe navigation decision-making in rough weather conditions requires an integrated system capable of analyzing real-time wave information together with wind, atmospheric pressure, ship motion, and positional data.

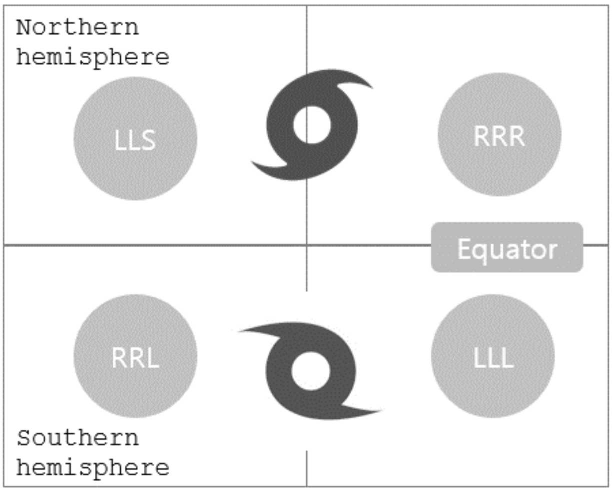

Figure 2: Recommended maneuvering according to ship position relative to typhoon movement

In the Southern Hemisphere, the maneuvering principles are reversed because tropical cyclones rotate clockwise. Consequently, the RRL (Right-Right-Port Quarter) and LLL (Left-Left-Port Bow) rules are applied as counterparts to the Northern Hemisphere rules.

3. Wave Observation System

The wave observation system used in this study consists of a marine X-band radar, a Radar Scan Converter (RSC), and a data processing computer. The system acquires real-time wave information based on radar transmission and reception signals and calculates wave parameters, including wave height, wave direction, wave period, and wavelength through Fast Fourier Transform (FFT)-based spectral analysis. Radar images are represented in a Plan Position Indicator (PPI) format using a polar coordinate system. For wave analysis, the radar images are transformed into a Cartesian coordinate system. Subsequently, the radar raw signals in the time domain are converted into spectral signals in the frequency domain to estimate the wave energy density (Ro et al., 2023).

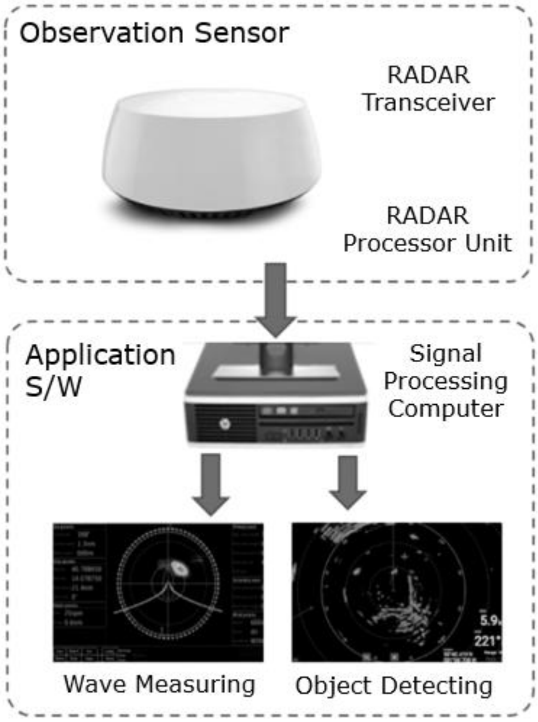

Figure 3: Configuration of Wave RADAR System

The significant wave height is calculated using the zeroth spectral moment of the wave spectrum as follows:

$$H_s = 4\sqrt{m_0} \quad (1)$$

where H_s denotes the significant wave height and m_0 represents the zeroth spectral moment of the wave spectrum.

Figure 4: Wave Observation System

The calculated wave information is subsequently linked to the heavy weather risk assessment module and utilized as input data for navigation decision support.
Figure 4 shows the Wave Observation System installed on a 9,000 GT vessel. The system is capable

of calculating wave height, wave direction, wave period, and wavelength in real time. In this study, the observed wave information was utilized as input data for the heavy weather risk assessment module and the proposed navigation decision support system.

4. Proposed Rough Weather Decision Support System

Figure 5 illustrates the overall architecture of the proposed heavy weather decision support system. The proposed system collects real-time marine environmental information using a Wave Observation System (WOS) and recommends appropriate heavy weather maneuvering strategies through a fuzzy-based heavy weather risk estimation module and an RRW (Recommend System under Rough Weather)-based maneuvering decision support module.

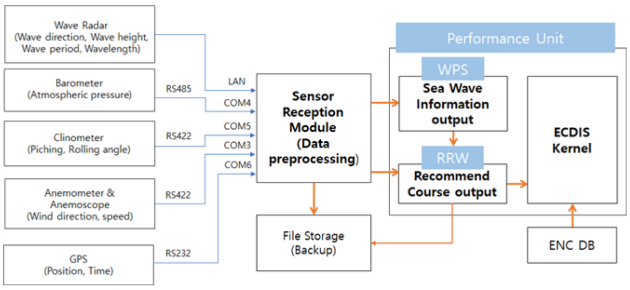

Figure 5: Overall architecture of the proposed heavy weather decision support system

The proposed system calculates heavy weather risk based on real-time sensor data and analyzes the current risk level of a vessel using a fuzzy inference-based risk assessment algorithm. Furthermore, the system determines whether the vessel is located within the Dangerous Semicircle or the Navigable Semicircle by analyzing the vessel's relative position with respect to the typhoon center and changes in wind direction. Based on this assessment, appropriate maneuvering methods are recommended.

The overall operational procedure of the proposed wave observation and heavy weather decision support system can be summarized as follows:

1. Real-time sensor data acquisition
2. FFT-based wave information extraction
3. Heavy weather risk estimation
4. Relative position determination with respect to the typhoon center
5. Maneuver recommendation
6. Provision of navigational decision support information

The calculated risk level and maneuvering recommendations are finally provided to navigators or remote operation systems to support safe navigation under heavy weather conditions.

4.1 Fuzzy-based Heavy Weather Risk Estimation

Although the conventional RRW algorithm provides maneuvering recommendations based on wind direction changes and wave conditions, it has limitations in quantitatively evaluating navigational risk. Furthermore, even under identical sea states, the actual level of risk may vary depending on vessel size. Therefore, a risk assessment method considering vessel characteristics is required.

To address this limitation, a fuzzy inference-based heavy weather risk estimation module was developed. Figure 6 shows the structure of the proposed fuzzy-based heavy weather risk estimation model.

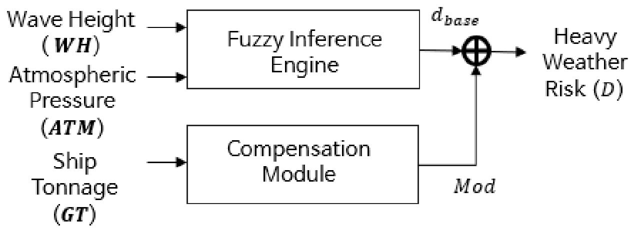

Figure 6: Fuzzy Risk Estimation Structure

The input variables of the fuzzy inference engine consist of significant wave height (WH) and atmospheric pressure (ATM). Wave height is one of the primary indicators representing the severity of sea conditions, while atmospheric pressure is an important meteorological parameter used to determine the proximity of the typhoon center. In general, the risk level increases as wave height increases and atmospheric pressure decreases.

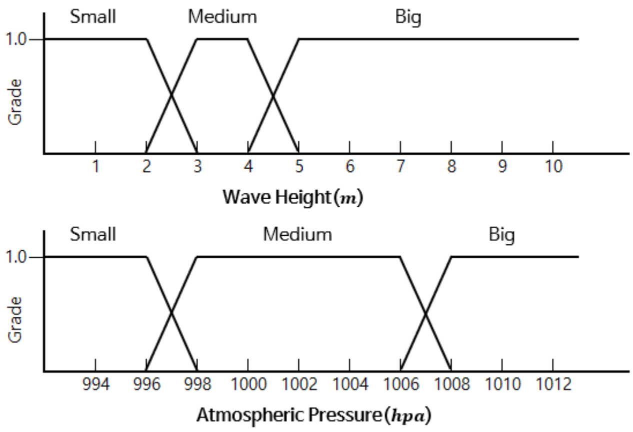

Figure 7: Membership functions for wave height and atmospheric pressure

Figure 7 presents the membership functions of the input variables. Wave height is divided into three fuzzy sets: Small, Medium, and Big. Atmospheric pressure is also classified into three fuzzy sets: Low, Medium, and High. As wave height increases, vessel motions and wave impacts become more severe, leading to a higher risk level. Conversely, lower atmospheric pressure generally indicates closer proximity to the typhoon center, resulting in increased navigational risk.

The fuzzy inference rules are defined as shown in Table 2. The output risk level is classified into five linguistic variables: Very Small (VS), Small (S), Medium (M), Big (B), and Very Big (VB). The rule base was established based on Dove's Law, practical heavy weather maneuvering guidelines, and consultation with experienced navigators. The input variables were intentionally limited to significant wave height and atmospheric pressure to evaluate the feasibility of the proposed decision support framework. In particular, conditions involving both high wave heights and low atmospheric pressure are assigned the highest risk level. (Yoon, 2022; Seol, 2015)

Table 2: Fuzzy Inference Rule

WH \ ATM	Low	Medium	High
Small	M	S	VS
Medium	B	M	S
Big	VB	B	M

For example, when the wave height is classified as Big and the atmospheric pressure is classified as Low, the vessel is assumed to be operating near the typhoon center under severe sea conditions. Therefore, a Very Big (VB) risk level is assigned. Conversely, when the wave height is Small and the atmospheric pressure is High, the sea state is considered relatively safe, resulting in a Very Small (VS) risk level.

Figure 8 shows the membership function of the output variable representing heavy weather risk. The fuzzy inference result is expressed using the five linguistic variables (VS, S, M, B, and VB) and is converted into a continuous risk value ranging from 0 to 1 through a defuzzification process. This enables the quantitative representation of heavy weather conditions and provides input data for the maneuvering decision support algorithm.

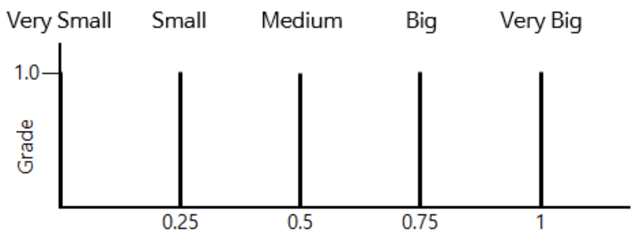

Figure 8: Heavy Weather Risk

Since the impact of rough weather may vary according to vessel size even under the same wave conditions, a ship-tonnage compensation module was additionally introduced. Figure 9 shows the membership functions for vessel tonnage, while Figure 10 presents the corresponding compensation values (Mod) assigned to each tonnage group. Vessels are classified into five groups: Very Small, Small, Medium, Big, and Very Big, based on the typical tonnage distribution of coastal and ocean-going vessels.

The final heavy weather risk level is calculated using the compensation value as follows:

$$D = d_{base} + Mod \quad (2)$$

$$D = \max(0, \min(1, D)) \quad (3)$$

Equation (3) clips the calculated heavy weather risk to the interval [0,1], ensuring that the final risk value remains within the normalized range of the proposed fuzzy risk model. In Equations (2) and (3), where d_{base} represents the basic risk level calculated through fuzzy inference and Mod denotes the compensation value determined according to vessel gross tonnage. Since the heavy weather risk index is defined within the range of 0 to 1, values exceeding the upper bound are assigned a value of 1, while values below 0 are assigned a value of 0.

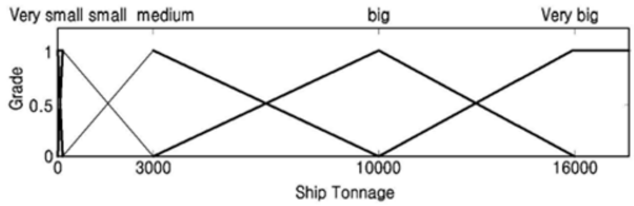

Figure 9: Membership function for Ship Tonnage Compensation Model

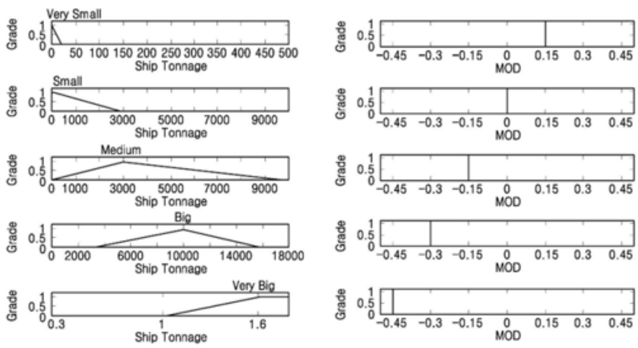

Figure 10: Ship Tonnage Compensation Model

Table 3: Ship Tonnage Compensation Values (Mod)

Ship Group	Mod
Very Small	+0.20
Small	+0.10
Medium	0
Big	-0.10
Very Big	-0.20

In general, larger vessels possess greater stability and superior motion characteristics than smaller vessels under identical wave conditions. Therefore, the compensation value is designed to reduce the calculated risk level as vessel size increases.

In this study, significant wave height and atmospheric pressure were selected as the primary input variables because they directly represent the severity of heavy weather and can be continuously obtained from the wave observation system. Wind information was intentionally excluded from the fuzzy risk estimation model because it is directly utilized by the RRW maneuvering algorithm for maneuver selection, thereby avoiding redundancy between risk estimation and maneuver decision.

The final heavy weather risk value calculated in this section is subsequently used as an input to the RRW-based maneuvering decision support algorithm described in the following section.

The proposed fuzzy model was intentionally designed with a limited number of input variables to verify the feasibility of integrating real-time wave observation data with rough weather maneuvering decision support. Future studies will incorporate additional environmental and ship-motion parameters to improve risk estimation accuracy.

4.2 Enhanced RRW Decision Support Algorithm

Safe navigation in heavy weather conditions requires not only the observation of the marine environment but also the assessment of the current risk level and the selection of an appropriate maneuvering strategy. Therefore, this study developed an RRW (Recommend System under Rough Weather)-based maneuvering decision support algorithm utilizing the results of the fuzzy-based heavy weather risk assessment.

Figure 11 illustrates the overall flow of the proposed Enhanced RRW algorithm. The conventional RRW algorithm determines maneuvering strategies based on wind direction changes and the vessel's relative position to a typhoon. In contrast, the proposed Enhanced RRW algorithm additionally incorporates the results of fuzzy-based risk assessment to determine whether the RRW procedure should be activated.

The system first calculates the heavy weather risk level using wave height, atmospheric pressure, and positional information. The calculated risk level is classified into five categories: Very Small (VS), Small (S), Medium (M), Big (B), and Very Big (VB). When the calculated risk level is classified as VS, S, or M, the vessel maintains normal navigation while continuously monitoring environmental conditions. This is because such risk levels are considered insufficient to require the execution of heavy weather maneuvering procedures.

In contrast, when the risk level is classified as B or VB, the system determines that the vessel has entered, or is likely to enter, a heavy weather environment and activates the RRW algorithm. Therefore, the fuzzy risk assessment result is not merely used as a risk indicator but also serves as a threshold for determining whether the RRW algorithm should be executed. The threshold was intentionally set to B because risk levels VS–M represent environmental conditions in which conventional navigation can generally be maintained, whereas B and VB indicate heavy weather conditions requiring active maneuvering according to practical heavy weather navigation guidelines.

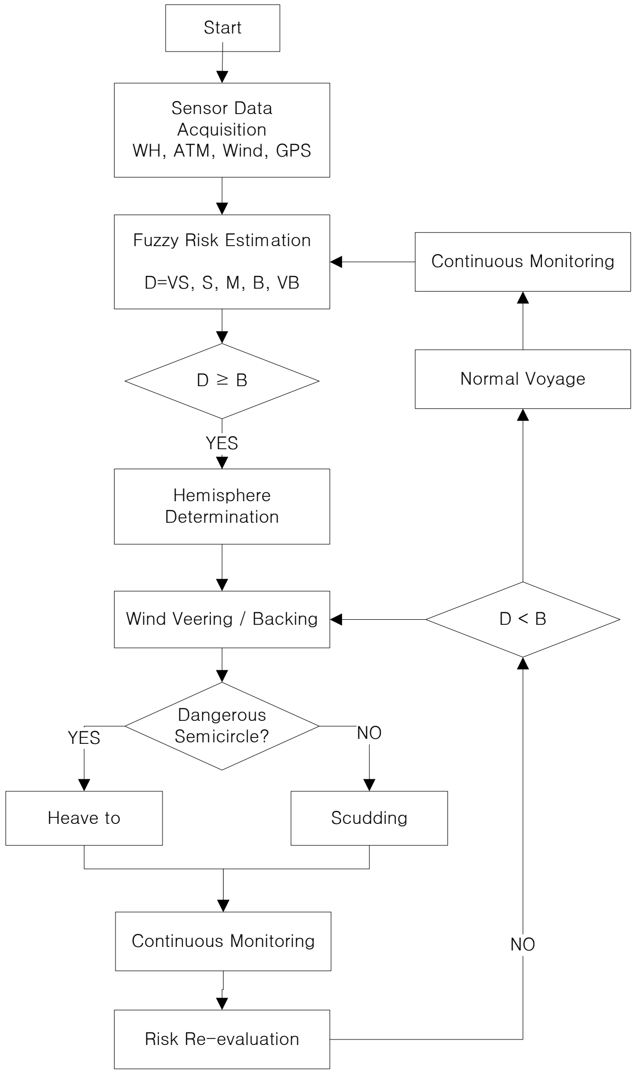

Figure 11: Enhanced RRW Algorithm based on Fuzzy Risk Assessment

The RRW algorithm is activated only when the estimated risk level is equal to or greater than B. The algorithm first determines whether the vessel is operating in the Northern or Southern Hemisphere using GNSS position data. Subsequently, the system analyzes clockwise wind shifts (veering) and counterclockwise wind shifts (backing) to determine whether the vessel is located within the Dangerous Semicircle or the Navigable Semicircle relative to the typhoon center.

When the vessel is located within the Dangerous Semicircle, the system recommends the Heave-to maneuver. Heave-to is a maneuvering technique in which the vessel maintains its bow toward the wind and waves while proceeding at the minimum speed necessary to retain steering control. This maneuver reduces wave impacts on the vessel and helps maintain a safe position relative to the typhoon center. In general, the vessel is maneuvered so that the wind is received approximately 30° on the starboard bow. The recommended ship heading is calculated as follows:

$$Ship's\ Heading = \theta_{wtd} - 30^{\circ} \tag{4}$$

If the wind true direction (θ_{wtd}) is less than 30°, the heading is calculated as:

$$Ship's\ Heading = 360^{\circ} + (\theta_{wtd} - 30^{\circ}) \tag{5}$$

On the other hand, when the vessel is located within the Navigable Semicircle, the system recommends Scudding. Scudding is a maneuvering technique in which the vessel proceeds before the sea while receiving waves from the quarter astern. This method allows the vessel to move away from the typhoon area more rapidly. In general, the vessel is maneuvered to receive the wind at approximately 130°–150° relative to the ship's fore-and-aft line (Yoon, 2022). In this study, 145° was selected as a representative value.

$$Ship's\ Heading = \theta_{wtd} - 145^{\circ} \tag{6}$$

If the wind true direction is less than 145°, the heading is calculated as:

$$Ship's\ Heading = 360^{\circ} + (\theta_{wtd} - 145^{\circ}) \tag{7}$$

During the execution of the recommended maneuver, the system continuously monitors wave height and atmospheric pressure and repeatedly recalculates the heavy weather risk level. If the estimated risk level decreases below B, the system determines that the heavy weather condition has subsided and terminates the RRW procedure. Conversely, if the risk level remains equal to or greater than B, the current maneuvering strategy is maintained while the risk assessment process continues.

Through this approach, the proposed system provides not only heavy weather detection but also risk-based maneuvering decision support. The system can be applied not only to conventional merchant ships but also to autonomous ships and remote operation environments.

While the conventional RRW algorithm determines maneuvering strategies solely based on wind direction changes, the proposed Enhanced RRW algorithm additionally incorporates fuzzy-based heavy weather risk assessment. Consequently, RRW procedures are activated only when actual heavy weather conditions are identified. This approach minimizes unnecessary maneuvering changes and provides more stable and reliable decision support for heavy weather navigation.

5. Simulation

To verify the performance of the proposed fuzzy-based heavy weather risk estimation algorithm and the Enhanced RRW maneuvering decision support algorithm, simulation experiments were conducted. The simulations were performed using a vessel with a gross tonnage of approximately 9,000 GT. Significant wave height and atmospheric pressure obtained from the Wave Observation System were used as input variables.

The simulation scenarios consisted of three different conditions: a normal sea state, an approaching rough weather condition, and a severe typhoon condition. For each scenario, the heavy weather risk level was calculated using the fuzzy inference engine, and the ability of the Enhanced RRW algorithm to recommend an appropriate maneuvering strategy was evaluated.

5.1 Scenario 1: Normal Sea State

Scenario 1 assumed relatively calm sea conditions. The input parameters were set to a significant wave height of 2.0 m and an atmospheric pressure of 1008 hPa. According to the WMO Sea State classification, this condition corresponds approximately to Sea State Grade 4 and can be regarded as a normal navigation environment.

The fuzzy inference result indicated a heavy weather risk level of Small (S). Since the estimated risk level was below the RRW activation threshold of Big (B), the system maintained Normal Voyage mode. Consequently, no heavy weather maneuvering procedure was executed, and only continuous environmental monitoring was performed.

5.2 Scenario 2: Approaching Rough Weather

Scenario 2 assumed that the vessel was entering the outer region of a typhoon. The input parameters were set to a significant wave height of 5.0 m and an atmospheric pressure of 1000 hPa.

The fuzzy inference result indicated a heavy weather risk level of Big (B). Therefore, the Enhanced RRW algorithm was activated. The system analyzed the vessel's relative position to the typhoon and the wind direction variation to determine whether the vessel was located within the Dangerous Semicircle or the Navigable Semicircle.

The simulation results showed that when the vessel was located within the Dangerous Semicircle, the Heave-to maneuver was recommended. This maneuver minimizes the possibility of the vessel being drawn toward the typhoon center and reduces wave impact loads acting on the hull.

5.3 Scenario 3: Typhoon Area

Scenario 3 assumed a severe rough weather condition in which the vessel had entered the typhoon area. The input parameters were set to a significant wave height

of 8.0 m and an atmospheric pressure of 994 hPa.
The fuzzy inference result indicated a heavy weather risk level of Very Big (VB). Accordingly, the system immediately activated the RRW algorithm and recommended an appropriate maneuvering method based on the vessel's relative position to the typhoon. When the vessel was determined to be located within the Dangerous Semicircle, the system recommended Heave-to. Conversely, when the vessel was located within the Navigable Semicircle, Scudding was recommended. These maneuvering strategies allow the vessel to move away from the typhoon center while minimizing vessel motions and structural loads. Table 3 summarizes the simulation results obtained for the three scenarios.

Table 4: Simulation Results of Proposed System

Scenario	1	2	3
Wave Height (m)	2.0	5.0	8.0
Pressure (hPa)	1008	1000	994
Risk Level	S	B	VB
RRW Execution	No	Yes	Yes
Recommended Action	Normal Voyage	Heave-to / Scudding	Heave-to / Scudding

The simulation results demonstrate that the proposed system can effectively estimate heavy weather risk based on wave height and atmospheric pressure and appropriately activate the Enhanced RRW algorithm when the estimated risk exceeds the predefined threshold. Furthermore, the system successfully recommends suitable maneuvering strategies according to the vessel's relative position to the typhoon, thereby supporting safe navigation under rough weather conditions.
Although X-band radar performance may degrade under heavy rainfall due to attenuation and clutter, the proposed system employs FFT-based spectral processing, temporal averaging, and filtering techniques described in Ro et al. (2023). Nevertheless, additional rainfall compensation and robustness enhancement techniques should be investigated in future work to improve system reliability under extreme weather conditions.

6. Conclusion

This study proposed a navigation decision support system for heavy weather operations based on real-time wave observation data. The proposed system utilizes an X-band radar-based wave observation system to collect marine environmental information, including wave height, wave direction, and wave period, in real time. Furthermore, a fuzzy-based heavy weather risk assessment method was developed to quantitatively evaluate the current sea state. In addition, an Enhanced RRW (Recommend System under Rough Weather) decision-making algorithm was implemented by incorporating a risk assessment function into the conventional RRW algorithm.
The proposed fuzzy risk assessment module employs significant wave height and atmospheric pressure as input variables and classifies heavy weather risk into five levels: Very Small (VS), Small (S), Medium (M), Big (B), and Very Big (VB). Furthermore, a ship-tonnage compensation module was introduced to reflect differences in risk levels according to vessel size under identical sea conditions. Simulation results demonstrated that the RRW algorithm is activated only when the estimated risk level exceeds the threshold of Big (B), thereby reducing unnecessary maneuvering actions and enabling more systematic heavy weather decision-making.
The proposed Enhanced RRW algorithm analyzes the vessel's relative position to a typhoon and changes in wind direction to recommend appropriate maneuvering strategies. Specifically, Heave-to is recommended when the vessel is located within the Dangerous Semicircle, whereas Scudding is recommended when the vessel is located within the Navigable Semicircle. The results indicate that the proposed approach can overcome the limitations of the conventional RRW algorithm, which relies primarily on qualitative judgment, and provide quantitative decision support based on heavy weather risk assessment. Consequently, the proposed system provides a practical framework for quantitative heavy weather decision support that can be applied not only to conventional merchant ships but also to Maritime Autonomous Surface Ships (MASS) and remote ship operation environments.
For MASS applications, the proposed system can be integrated into the onboard autonomous navigation controller or remote operation center as a decision-support module. By continuously analyzing real-time wave observation data and environmental information, the system can provide appropriate heavy weather maneuvering recommendations or support autonomous maneuver planning under severe sea conditions.
Although the proposed system demonstrated the feasibility of integrating wave observation data with heavy weather decision support, the present study has several limitations. The fuzzy rule base was constructed using representative environmental conditions and expert knowledge, and the simulation was performed using a limited number of representative scenarios. Therefore, further validation using long-term onboard sensor data collected under various sea states is required.
Future research will focus on enhancing the fuzzy rule base and risk assessment model using long-term data collected from wave observation systems installed on actual vessels. Continuous time-series sensor logs collected from actual merchant vessels will be used to validate the dynamic performance and

robustness of the proposed Enhanced RRW algorithm under continuously changing heavy weather conditions. Subsequently, more comprehensive heavy weather risk prediction models will be developed by incorporating wind speed, wind direction, vessel motion information (roll and pitch), and typhoon forecast data. Finally, sea trials involving various vessel types and operating environments will be conducted to verify the practical applicability and reliability of the proposed system.

7. Acknowledgements

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