Towards an Online Decision Support System to Improve Collision Risk Assessment at Sea

Luman Zhao, Sai Rana Thattavelil Sunilkumar, Baiheng Wu, Guoyuan Li, *Senior member, IEEE,* and Houxiang Zhang, *Senior member, IEEE*

***Abstract*—The increasing ship speed and unpredictable environmental perturbations raise the difficulty for situation awareness and collision avoidance, for instance, when maneuvering in narrow and busy surroundings. Providing decision support for these operations automatically and timely is thus of great concern in terms of ship safety. To achieve it, we developed an online decision support system (DSS) to provide navigators with intuitive and reliable solutions such as a collision risk, point of collision in real-time. More specially, the collision risk for each target ship is colored-coded and the ship domain is marked by the heat map, which can remind the navigators of the surrounding situations intuitively. Afterward, a comparative case study between with and without decision support was conducted to verify the effectiveness of the DSS during the busy water navigation process around a high-fidelity simulator. Experiment results show that the collision risk can be significantly reduced with the help of the proposed DSS. It has the potential to be used onboard as a complementary service in the near future.**

***Index Terms*—Online decision support system, human-machine interfaces, collision avoidance, collision risk assessment.**

I. Introduction

THE transition towards digitalization is speeding up in the maritime industry. Digitalization makes it possible to distribute or processes digital data. Leveraging digitized data and digital technologies can primarily increase the efficiency of existing processes and enable new processes. The maritime industries are following this transformation and are benefiting from improving efficiency and quality of manual decision-making and processes.

In navigation, there are tracks be to followed, but in collision avoidance, not such tracks can be prepared in advance and rise a challenge to the whole industry, because the International Regulations for the Prevention of Collisions at Sea (COLREGs) [1] are the only mechanism by which navigational risk is controlled. If the rules are not followed the risks increase. As a result, collision avoidance is highly dependent upon seamanship and proper look-outs. In addition, navigation is inevitably influenced by the wind, wave, sea currents, or other perturbations at sea, which makes the maritime operations more and more difficult. How to automatically and timely provide decision support during the navigation is crucial and necessary.

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Luman Zhao, Sai Rana Thattavelil Sunilkumar, Baiheng Wu, Guoyuan Li, and Houxiang Zhang are with the Department of Ocean Operations and Civil Engineering, Norwegian University of Science and Technology (NTNU), Aalesund, Norway. (e-mail: luman.zhao@ntnu.no, sairt@stud.ntnu.no, baiheng.wu@ntnu.no, guoyuan.li@ntnu.no, hozh@ntnu.no).

The ship bridge layout is filled with equipment and tools used for navigation and collision avoidance. From the ship management point of view, during the past 20 years, there is little changes of the navigation equipment and resources onboard, such as Electronic Chart Display and Information System (ECDIS), and Automatic Radar Plotting Aid (ARPA). The ECDIS is a geographic information system used for nautical navigation. It incorporates and displays information such as speed over ground (SOG), course over ground (COG), and so on, that from the Global Navigation Satellite Systems (GNSS), Automatic Identification Systems (AIS), and other navigational sensors. With the use of the electronic chart system, ECDIS can greatly eases the navigator’s workload with the ability of situation awareness. However, it can surely help but not be used for collision avoidance. As collision avoidance rules and situations are mainly based on how we see the ship and not on how they are moving. Navigators refer to the information such as speed through water (STW), course through water (CTW), and navigation lights, and take collision avoidance actions according to the requirements of COLREGs. COG can tell navigators in when and where a collision will occur, but it won’t tell the aspect of the other ships in the case of currents. CTW can tell navigators the heading/aspect of the other ships, so that evasive action can be taken in accordance to COLREGs.

While ARPA automatically acquire and display the positions, speeds, and courses of a own ship (OS) and target ships (TSs) in the vicinity and select a proper course for the own ship by avoiding collision. It is used to detect the collision candidate according to the information "how we see the ship" of STW and CTW, then to assess the risk of collision with the closest point of approach (CPA) to OS, and enable navigator to see proposed maneuvers.

However, in very busy areas, such as harbours, rivers and archipelagos, the need for a high update rate mode ARPA is evident. For example, when performing an urgent task with multiple responsibilities, the search and rescue vessel that receives a distress call is obligated to assist others in distress at sea with a top speed close to 40 knots. In such situations, a rescue path planning and collision avoidance are significant factor in ensuring navigation safety and efficiency. Consequently, how to assess the collision risk and display it in a intuitively way is essential to the safety and efficient navigation.

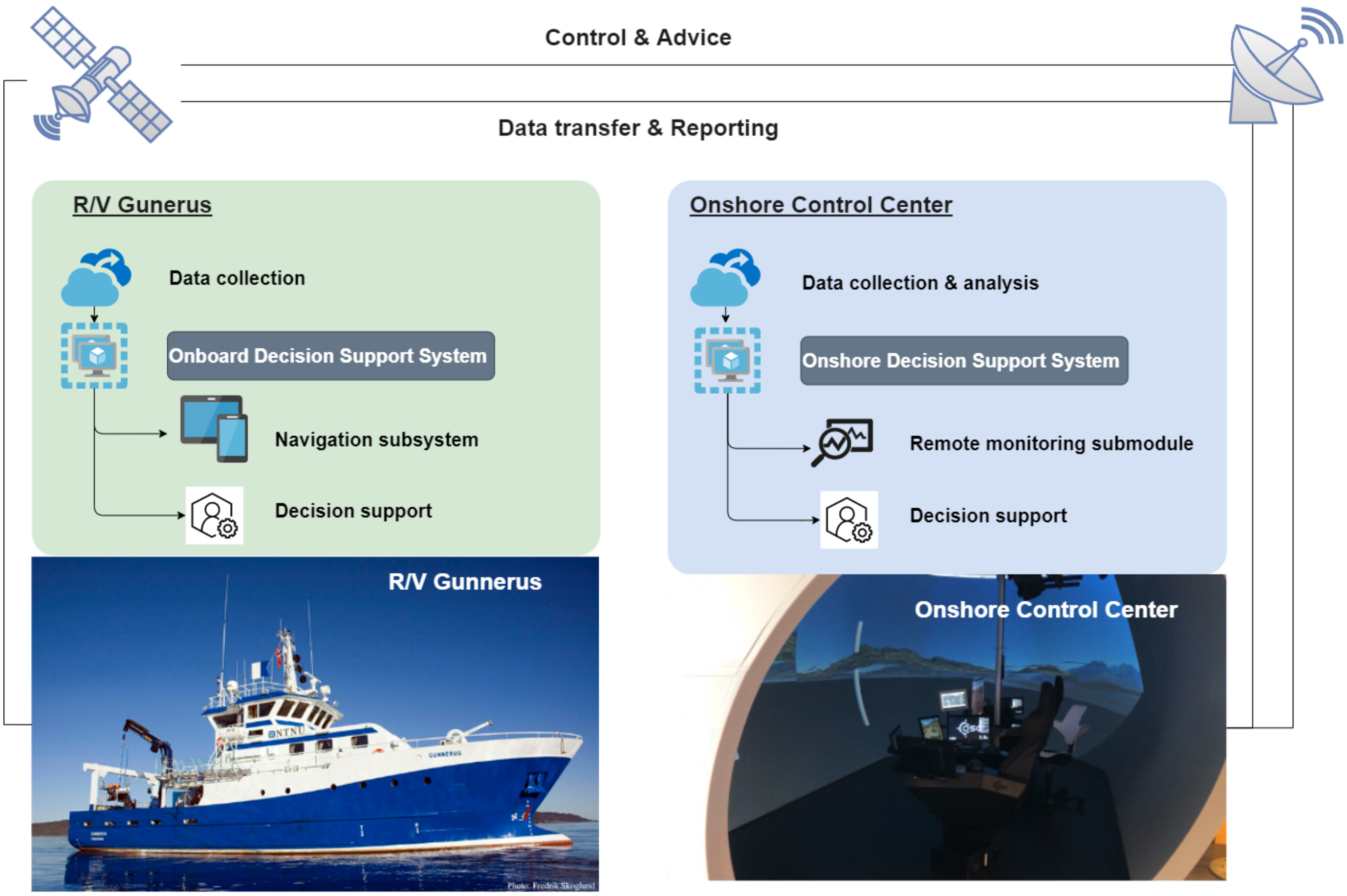

Fig. 1: Two ways of the use the decision support system.

Due to the complex nature of specialized systems, with integration mechanisms with sensors, real-time monitoring the relevant data for analysis and decision making as become a significant challenge. To ensure safety and improve efficiency during maritime navigation, we aim to develop a Decision Support System (DSS) to provide navigators with intuitive and reliable solutions in real-time. The DSS will help with collision avoidance and trajectory planning for congested water operations at large. The development of an onboard DSS will be a gradual and iterative process subject to extensive testing and simulation. Hence, we first assesses the system from a high-fidelity simulator through a specialized strait crossing application, then improve it by collecting the navigators' first-hand experience, finally have a overview of how the DSS is supporting with the navigator on the simulator with the developed real-time decision support tool.

The system will be implemented to serve for ships that are either onboard or onshore for safety and reliability enhancement, which is described in Fig. 1. In current industrial practices, mainstream data sources include GNSS, AIS, and other navigational sensors. Data are often reorganized and plotted on the onboard graphical interfaces, such as ARPA and ECDIS to assist navigators efficiently. The proposed DSS can complement the navigation equipment to provide various support, such as collision risk level, reference trajectory, etc., to the navigators in an intuitive way. Furthermore, such data sets can often be collected from the sensor systems and transferred to the onshore control center, which can be used for remote monitoring and prediction assurance. As a result, the proposed DSS has the potential to be facilitated onboard or onshore control centers for future vessels, which depends on the data resources and interface. Especially, this technology can also be deployed in a Vessel Traffic Service (VTS) system onshore to assist maritime traffic controllers in managing marine traffic proactively to improve the safety of navigation.

The rest of this article is organized as follows. In Section II, we provide a comparative review of work related to our study. In Section III, we introduce the configuration of the proposed DSS. To analyze the benefits of our system, we perform extensive experiments and comparative analysis in Section IV. Finally, Section VI concludes this paper.

II. Related Works

Navigational situation assessment is essential for maritime traffic management related to safety at sea. Qualitative studies for collision risk assessment have been carried out for the significant development of automatic navigation. The methods of collision risk assessment can be performed by either detecting the potential violation of the ship domain or defining a collision risk index (CRI) based on the distance to the closest point of approach (DCPA), time to the closest point of approach (TCPA), and others such as encounter angle and the ratio of speed. One representative risk assessment method is CRI which combines multiple factors to determine the degree of danger of each surrounding target ship for collision alerting. The CRI criterion is generally from navigators' knowledge and experience that ranges from 0.00 to 1.00. For example, [2] used the fuzzy logic method to calculate the CRI by considering the parameters including DCPA, TCPA, relative distance, relative bearing, and the difficulty of maneuverability between the encountered two ships, etc. [3] summarized a navigational pattern that was identified with respect to a CRI by interpreting data collected from the GPS and AIS.

The ship domain is the other criteria in assessing navigational safety at sea for collision avoidance purposes. The ship domain is an area surrounding the ship that the navigator preferred not to violate. Referring to a well-known definition of ship domain by [4]: "the surrounding effective waters which the navigators of a ship want to keep clear of other ships or fixed objects." Generally, the ship domain boundary consists of four radii, i.e., fore, aft, starboard, and port, which sufficiently consider factors affecting the domain. [5] extended and generalized a fuzzy boundary of the ship domain and also compared the criteria of fuzzy ship domain and CPA. [6] employed the fuzzy ship domain concept to quantitatively assess the collision risks by several risk indices according to the AIS data. On this basis, [7] assessed the collision risk by using the ship domain while considering the COLREGs as well as other ships from different perspectives. Similarly, based on the fuzzy rules, [8] also presented a ship domain-based collision risk assessment method that complies with COLREGs. [9] proposed a quaternion ship domain method to determine the domain sizes. [10] derived the unified measure of collision risk from the concept of ship safety domain. [11] constructed a unified framework of ship collision risk assessment based on the different types of ship domain. [12] examined the impact of ship size and speed on domain shape and size for collision avoidance, where the overlaps of ship domains indicate a higher likelihood of ship collisions.

However, the existing CRI-based method and ship domain method have situation awareness uncertainties. To overcome the shortcoming of each method, [13] proposed a hybrid method by combining the advantages of both methods for collision avoidance. [14] improved the CRI by correcting the values of the DCPA, TCPA and utilized a polygon to represent the ship domain based on the AIS data. [15] presented a time-varying collision risk measure, which reflects not only the dangerous level of the approaching ships but also the difficulty of avoiding collisions.

In this study, we not only concentrate on the methodology of the risk assessment, but onboard decision support system based on it. As a counterpart to the term DSS for the maritime vehicle, the advanced driver assistance systems (ADAS) for ground vehicles have been developed rapidly in recent decades [16]. An evolutionary roadmap of the ADAS can be found in [17]. Similar research interest for trains operating along railways has been studied by [18]. Compared with ground vehicles, collision avoidance for maritime vehicles has more challenges due to its unpredictable environment. Moreover, in such encounter situations, there are no tracks to follow that highly rely on the seamanship and navigators' experience. By eliminating human error from the equation, developing a DSS for collision avoidance is expected to enhance situation awareness, improve collision risk prediction, and automate the decision-making process. In conclusion, how to support the navigator precisely, immediately, practical, and obvious is our primary goal in this study. There are a huge number of research focused on collision risk assessment with the different domain of methods. Limited studies [19][3] have been convinced of their effectiveness in human-in-the-loop experiments. While ensuring the accuracy of collision risk assessment, we adopted the position of collision (POC) concept and color-coded CRI in our system to predict the future collision which can intuitively give the navigators the alarm. Both the human-centered design received good feedback from the navigators. Based on it, we further developed a portable DSS that can be implemented on the ship onboard and in the remote control center. It raises the potential to implement it in the real world.

III. Configuration

In congested waters, where ships are navigating with frequent trajectory changes, a safe situation can suddenly become critical. Under these situations, the ship should pay careful attention to the encounter situations with high collision risk between the OS and TSs. Therefore, to help with the navigators taking appropriate action early, the proposed DSS can evaluate the collision risk in real-time and present the information in an intuitive way. Here, each vessel treats itself as the OS from the first-person perspective; the other vessels are the TSs for ease of expression.

A. Overview of the functionality of the DSS

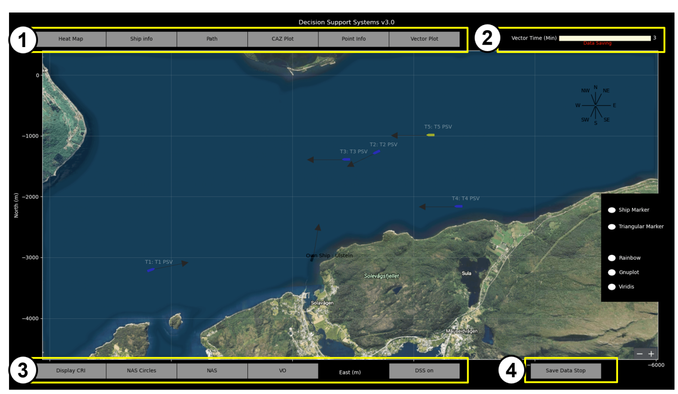

Fig. 2: Layout of the proposed decision support system.

Fig. 2 shows a graphical user interface (GUI) of the proposed DSS. It consists of four main functions, including Information display, Ship vectors, Decision support functions, and Data saving, that indicate in different areas.

1) Information display: Heat map and Ship information
   - **Heat map** visualizes the heat map of the each TS based on its ship domain.
   - **Ship information** shows the specification of each TS.

2) Ship vectors: Vector Length (Time)
   - **Vector Length** represents the vector with distance the ships will travel during the selected time interval and direction of the true course of each ship.
3) Decision support functions: Display CRI, NAS Circles, NAS, and VO
   - **Display CRI** is used to plot the collision risk index for each TS in real time.
   - **NAS Circles** is used to provide various safe passing distance.
   - **NAS** is used to activate the risk assessment function.
   - **VO** is used to plot the suggested collision free path according to the velocity obstacle method.
4) Data saving: Save Data
   - **Data saving** is used to save the historical data.

B. Collision risk assessment

The main objective of the DSS is to provide the collision avoidance support for the navigators in complex situations. Fig. 3 shows an example of how the system works. A ship is crossing a strait where four TSs are approaching from its starboard side, and one TS is approaching from its port side. It is trying to avoid the collision with the TSs and arriving at the destination on time. When activate the NAS function, it will plot the point of collision (POC) which indicates the future collision location of the OS with TSs. At 19:51:45 (UTC), a red circle of POC is highlighted on the screen where collisions will occur. Meanwhile, each TS is colored according to the CRI value. This information is promoting the navigators to avoid the collision with the TS2 (red with high risk) as it poses a threat to the OS. Then the OS can take the action to starboard while complying with the COLREGs. At 19:51:53 (UTC), the collision alert with TS2 (blue with low risk) has been lifted. If the OS continuously turn to starboard instead of keeping its course or speed, the DSS will give a high risk alert with the TS4 (red with high risk) in real-time. Consequently, to identify the risk level in a concise manner, we adopted the color-coded CRI approach and presented it to the navigators in an intuitive way of situation awareness.

1) POC and ship domain: POC is the point on the heading vector line at which a collision will take place. It can be derived by using a true motion plot and observing where TS's course intersects with the heading marker when the CPA is zero. The distance to the POC is measured from OS to the position of the future collision and can be calculated by multiplying TCPA with the speed of OS v_{os}. Here, TCPA is the time will take to reach the POC, which is considered safe and prudent for the prevailing conditions.

We defined the ship domain by considered the vessel's length and speed changes for maneuvering the ship. Based on the studies [12] [20], length has been taken as the main factor and the speed as the corrective factor. The ship domain can be simplified in Eq. 1.

$$r = f(L, v) \tag{1}$$

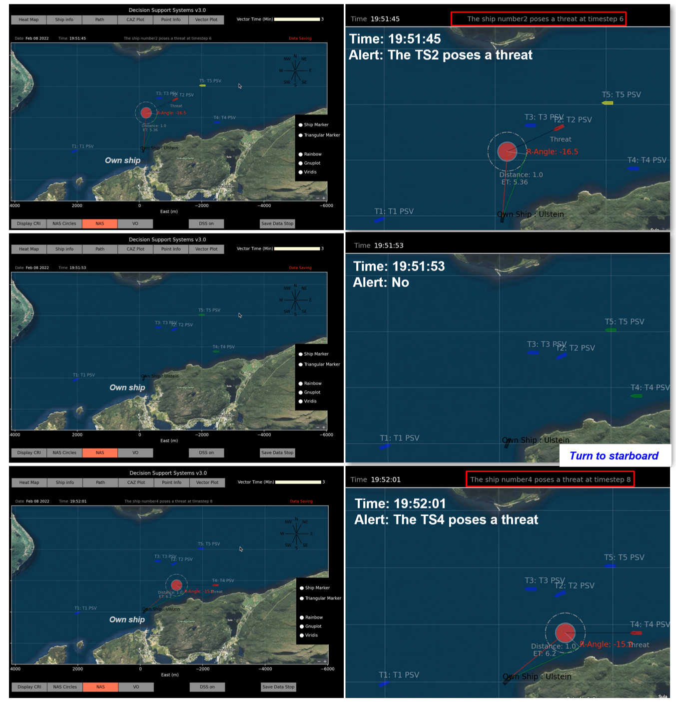

Fig. 3: Snapshot of the simulation environment where the OS is crossing a strait where multiple TSs are approaching.

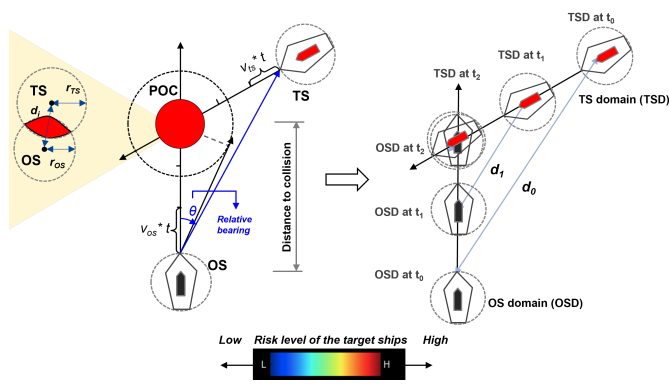

Fig. 4: Left: Ship domain of OS is intersecting with ship domain of TS, illustration of relative bearing; Right: process of collision detection.

2) Collision detection: We utilize the knowledge gained from POC and ship domain in developing the strategy of collision detection. When activating the function of "Vector Length", we can select the time interval t for plotting the future position of each ship. The length of each vector $v*t$ represents the future length after the selected interval, and the direction of vector represents the true course of the ship. In the "NAS" mode, the POC between the OS and the TSs can be recognised if the end of the TSs' vector lies in a direction which points to the end of the OS's true vector. These information is marked as a red circle to alert the navigators in real-time. The closest distance of the pairwise encounters can be used to find the possibility of collision in Eq. 2. Where d_0 and d_1 represent the distances of each time interval. These distance values give the navigator an overview of the closing distance between the

OS and the TS in future time frames.

$$d_i = min\,(d_0, d_1, d_2, ...) \tag{2}$$

As illustrated in Fig 4, if the minimum distance between OS and TS is smaller than the sum of the two ship domains, $d_i < r_{TS} + r_{OS}$, which means the circle of domain OS is intersecting with the circle of domain TS. In a word, the overlapping of ship domains DI is one of the important factors that can be used to indicate the risk level between the OS and the TS. More specifically, the process of risk assessment is performed by the fuzzy logic. The determined fuzzy sets make up a criterion for assessment of a navigational situation, the criterion that enables continuous assessment of the level of safety. The collision risk can be calculated by adding three factors with its weights accordingly. The factors consist of the overlapping of ship domains, the minimum distance between the OS and TS, and the TCPA. The equation used for this study is given as in Eq. 3:

$$CRI = w_{DI} \times DI + w_{d_i} \times d_i + w_{tcpa} \times tcpa \tag{3}$$

where w_{DI} denotes the wight factor for the domain intersection; w_{Dv} denotes the wight factor for closest predicted distance; and w_{tcpa} denotes the wight factor for the minimum time to collide. As the proposed DSS is meant to be used by the navigator for real-time support, the system should possess the ability to be used with a single glance or should be easily understandable by the navigator. To achieve this, we devised a color-coded CRI approach, where the CRI index value of each TS is color-coded from low (L) to high (H), and presented to the navigator in a concise manner.

θ denotes the relative bearing, which refers to the angle between the OS's heading direction and the location of TS. It is an important factor to identify the crossing type and is mainly related to the ease of taking collision avoidance actions compliant with COLREGs. The relative bearing angle displays on the screen of the DSS.

IV. Implementation and simulation results

To improve the safety and efficiency of handling more complex and risky operations, we proposed an integrated simulation framework for evaluating the proposed DSS, as shown in Fig. 5. A practical example that demonstrates the usage of the DSS in maritime navigation is based on the data from a high-fidelity simulator. The simulator provides realistic training scenarios that would have been impossible to carry out because of the ships' high speed and safety procedures. The selected maneuvering scenarios, multi-ship collision avoidance, will take place in Solavågen-Festøya and be simulated, involving multiple ships and various weather situations. We invited several nautical students to test the system. They tried maneuvering a vessel through the strait while avoiding several target ships on the scene. Meanwhile, the developed DSS can collect data from the simulator via signals following the WebSocket protocol, including the OS's GPS and AIS information. The DSS will then process the collision avoidance and serve as a guidance system onboard to provide various support intuitively. These navigators took part in two operation assignments using different training types: one is the traditional navigation type, and the other is the proposed way of using DSS. The result will then be used for verification and further improving the proposed DSS.

A. Simulation setup

1) Simulator: The simulator provides realistic training scenarios that would have been impossible to carry out because of the high speed and safety procedures of the ships. Generally, it can be used for training, research, and other purposes through a sophisticated visual environment that entails maximum realism exercises. In this study, we used a simulator for validating the developed DSS, which is shown in Fig 6. It is built by Offshore Simulator Centre AS (OSC) and is used as the remote control centre in NTNU Aalesund research laboratory. Equipped with a bridge for controlling the thrusters of the ship with a maritime lever, it can perform virtual prototyping and remote monitoring of onshore operations [21].

2) Interface: The primary task of navigation is to conduct a ship efficiently and safely along an assumed trajectory. Practical solutions to collision situations depend on sufficient data information. The developed DSS can collect data from the simulator via signals following the WebSocket protocol, which has a transmission rate of 1Hz. The collected data includes the GPS and AIS information of the OS. In this data processing stage, it is converted to meaningful information such as POC, the risk level of TSs, reference trajectory, etc. It can be served as a guidance system onboard to provide various support in an intuitive way. Finally, we prototype the algorithm on a Raspberry Pi board with a DSS panel display.

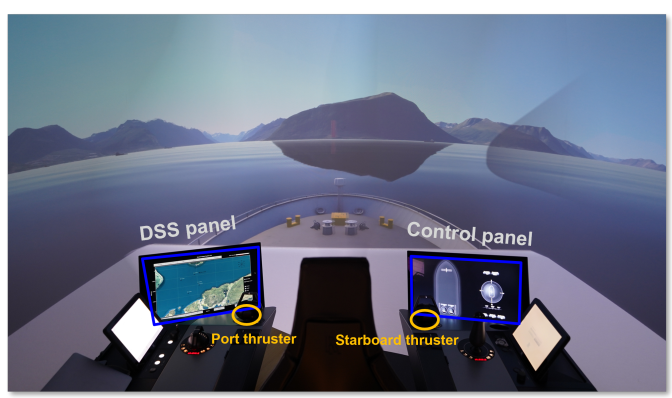

Fig. 6: Simulator in the research lab at NTNU Ålesund.

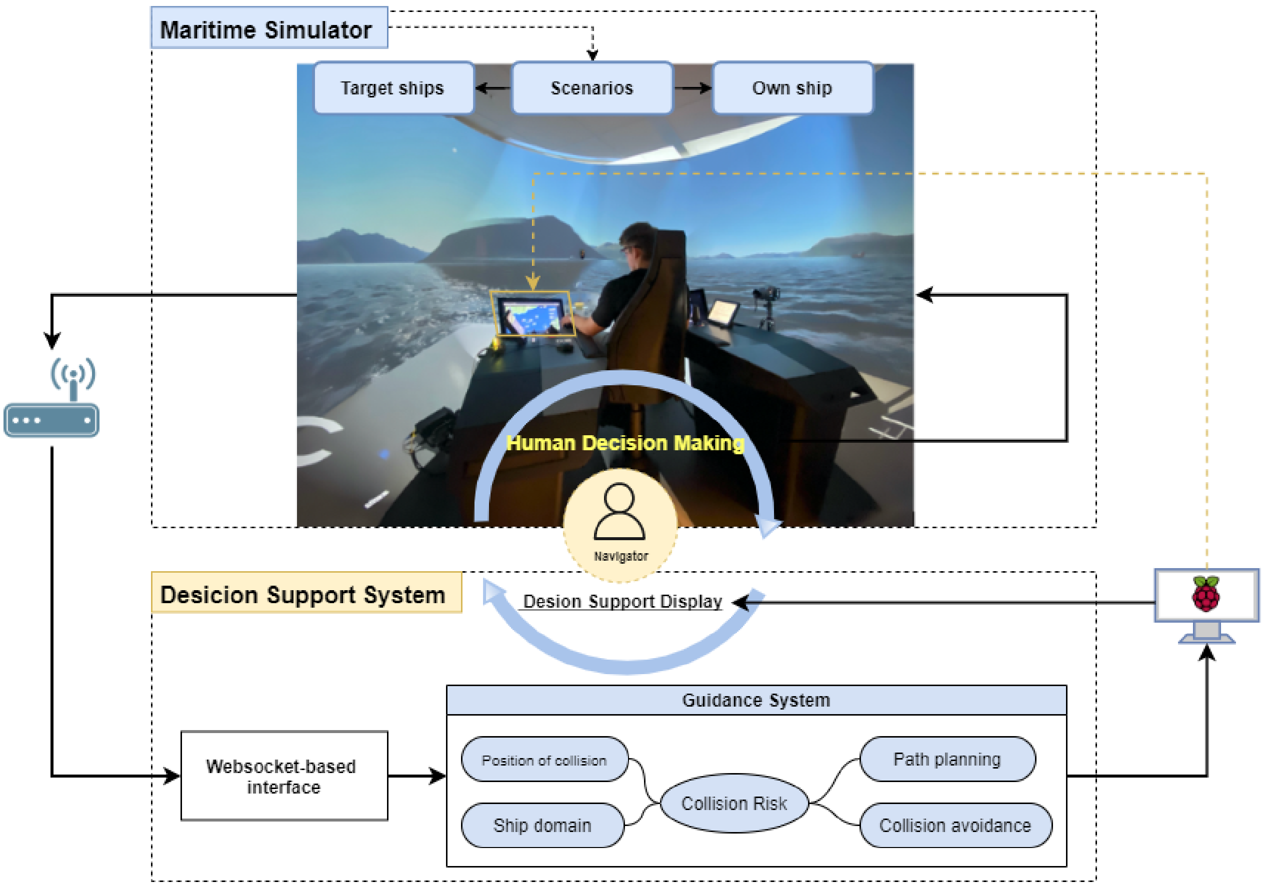

Fig. 5: Implementation the DSS in the simulator.

B. Multi-ship environment situation

No	Name	Speed [Knots]	Orientation [Degrees]
TS1	PSV UT 754 WP	5.5	-110
TS2	PSV UT 751 E	5.5	65
TS3	PSV 33000CD	5.5	90
TS4	PX 105 RMY	5.5	90
TS5	PSV UT 776 CD	5.5	90

Fig. 7: Simulation scenario with multiple target ships.

For testing the DSS, a fjord crossing scenario is set up in the simulator. The simulator can thus reconstruct the current state of the ship's position, orientation, and speed. The layout of the scenario is depicted in Fig.7. The OS departs from port Solavågen and arrives at port Festøya. Meanwhile, five TSs are approaching from the OS's starboard and port sides with the constant heading and speed. The OS has a responsibility to comply with COLREGs in this situation. For instance, Rule 15 of COLREGs deals with two vessels approaching from about 3 degrees off either bow, to 22.5 degrees aboft either beam. A vessel that has another on her starboard side shall actively avoid the other. The OS needs to keep a good lookout and take the action to avoid the possible collision with TS2,3,4, and 5.

C. Comparison study with and without DSS

The purpose of the comparison study is to illustrate the performance of the DSS. The simulations consider a multi-obstacle collision avoidance as shown in Fig.7. Several nautical students were assigned to take part in the experiment using different training types. Each student (navigator) took three tries: the first one and second tries were performed while deactivating the "NAS" function; and the last tries was performed by activating the "NAS" function. In the "without NAS" tries, the navigators were allowed to refer to the panel where displaying the map and position of both OS and TSs. As the navigators need to take time to familiarize themselves with the simulator and simulation scenarios, we decided to abandon the simulation result of the first attempt. We selected the results of the second tries and third tries of those three navigators and compared the collision risks of each TS. The comparison study between with DSS and without DSS is represented in Fig. 8 and Fig. 9.

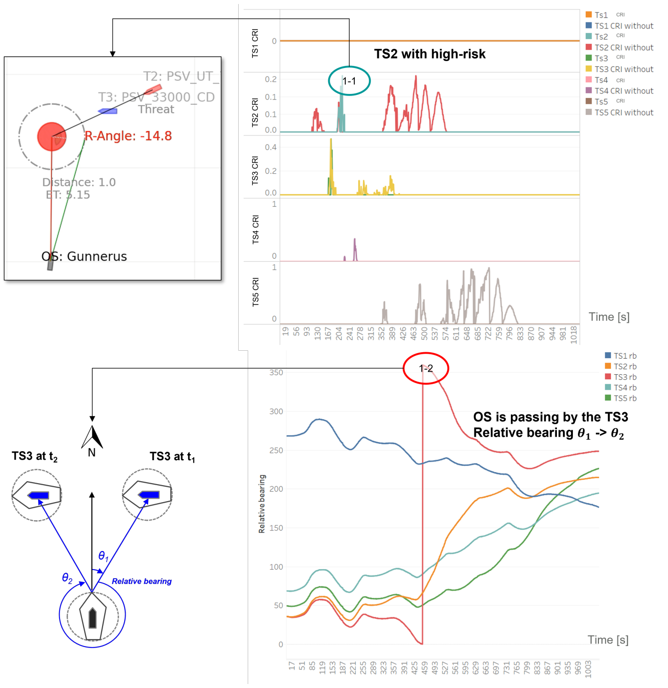

Fig. 8: Case 1: simulation results of with and without the DSS. Top: collision risk of each TS; Below: relative bearing of each TS with the OS.

To illustrate the full procedure of how the collision avoidance performs, we utilized the results of relative bearing for each TSs in the case "with NAS". As illustrated in Fig. 8, when the simulation starts, TS2,3, and 5 have the relatively higher collision risk with the OS rather than the other two ships. The navigator was continuously maneuvering the OS and heading to the destination, the three ships were approaching with different relative bearings of 35, 48, and 49 degrees. After a time, the collision risk of TS2 is gradually increasing to 0.1, and the collision risk of TS3 is gradually increasing to 0.4 next, which can be seen in the "without NAS" result.

In the "with NAS" mode, when the collision risk of TS2 increased to 0.2, the navigator can receive the alert from the DSS and take the proper action to avoid the collision. As shown in 1-1, the DSS displayed the POC which marked by a red circle and color-coded TSs where TS2 colored with red and TS3 colored with blue at the same time. Meanwhile, the collision risk with other obstacles can be reflected by heat maps, which are also regarded as a reference to navigators. These dynamic information enables the navigators to monitor and change the ship's route in an effective way whilst being provided essential information. When the navigator noticed the collision risk with TS2 on the screen, he attempted to change course to starboard in compliance with its responsibility to keep clear according to COLREGS. We can find the evidence from the relative bearing of TS3, which was changed to 360 degree as shown in 1-2. This sudden change indicated the moment when the OS was passing by the TS3. According to the comparison results of with and without DSS, we can conclude that the collision risk of TS2,3, and 5 were significantly reduced with the supported by the DSS.

V. Discussion and Conclusion

The main goal in this study is to develop an online decision support system to provide navigators with intuitive and reliable solutions in real-time. It will help with collision avoidance for congested water operations at large. During the navigation, the accuracy of data and suitable decision support presented to the navigators is essential for the correct situation assessment and their decisions. Nowadays, the navigational bridge of a ship features several devices that are supposed to assist the navigator in sailing safely. The current navigation systems are presently used to perform mainly information functions and correspondingly, to some extent, provide aid in safe vessel conduct. However, few of the known systems displays to the navigators complete solutions to a collision situation that are worked out in relation to all ships in the vicinity of their ship. After taking tries of the proposed DSS, we got the following comments from the navigators: "in my perspective, the color-coding for identifying the risk vessel is very novel and useful for the situation awareness," "such portable product seems can be complementary with the typical equipment, it is helpful for better decision making." In conclusion, as a complementary system for the ECDIS, and ARPA, the developed system enables the navigators to take the right actions at the right time, enhancing safety and efficiency by automating specific tasks.

As far as the DSS has been tested robust and reliable, we will move to the on-site validation stage on NTNU's research vessel, R/V Gunnerus. Currently, we have built an interface to the sensors onboard. It is expected to validate the system in the real ship applications.

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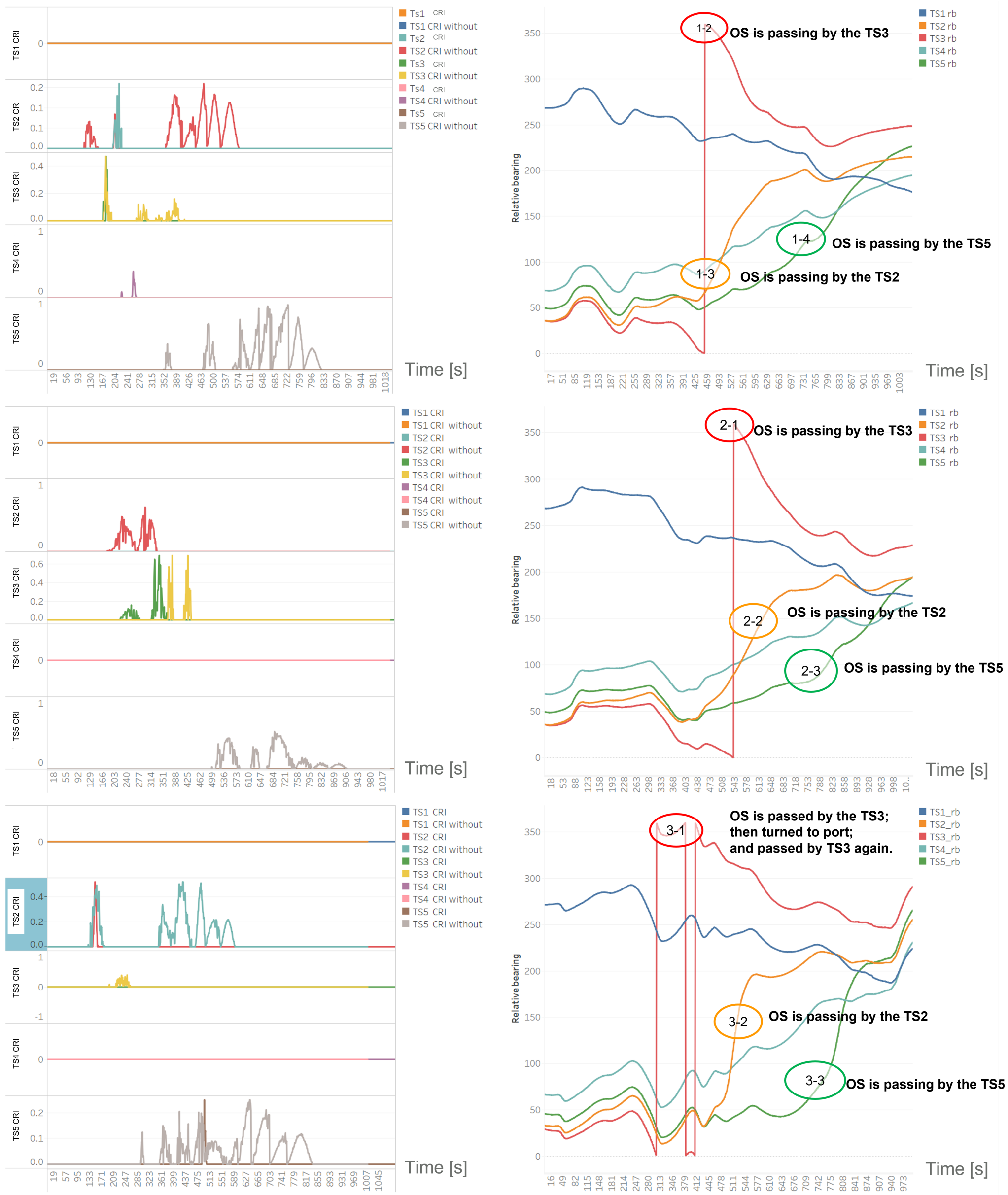

Fig. 9: Case 1, 2, and 3: simulation results of with and without the DSS.

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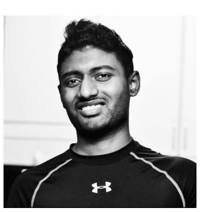
Luman Zhao received the B. Eng. at Department of Naval Architecture and Ocean Engineering, Mokpo National University, Korea, in 2012; the M. Sc. at Department of Naval Architecture and Ocean Engineering, Mokpo National University, Korea, in 2014; the Ph.D. degree at Department of Naval Architecture and Ocean Engineering, Seoul National University, Korea, in 2019. She is currently a post-doctoral research associate with NTNU, Ålesund, Norway, as a member of the Intelligent Systems Laboratory, Department of Ocean Operations and Civil Engineering. Her research interests include autonomous ship maneuvering, deep reinforcement learning, hardware-in-the-loop simulation, and optimization.



Sai Rana Thattavelil Sunilkumar received the M. Sc. at Department of Ocean Operations and Civil Engineering from Norwegian University of Science and Technology (NTNU), Ålesund, Norway, in 2022. His research interests include autonomous navigation and graphic visualization.

Baiheng Wu received the B. Eng. in naval architecture and ocean engineering from Tianjin University, Tianjin, China, in 2016; the M. Sc. in marine cybernetics from Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in 2019. He is currently pursuing the Ph.D. degree with NTNU, Ålesund, Norway, as a member of the Intelligent Systems Laboratory, Department of Ocean Operations and Civil Engineering. His Ph. D. project focuses on the human-in-the-loop learning and control for the autonomous maneuvering. His research interests extend to control theory, optimization, and machine learning algorithms and their applications in the maritime industry.

Guoyuan Li received the Ph.D. degree in computer science from the Department of Informatics, Institute of Technical Aspects of Multimodal Systems, University of Hamburg, Hamburg, Germany, in 2013. In 2014, he joined the Department of Ocean Operations and Civil Engineering, Intelligent Systems Laboratory, Norwegian University of Science and Technology (NTNU), Ålesund, Norway, where he is currently a Professor of Ship Intelligence. His research interests include modeling and simulation of ship motion, autonomous navigation, intelligent control, optimization algorithms, and locomotion control of bio-inspired robots. He has published more than 70 articles in these areas.

Houxiang Zhang is a full Professor at the Department of Ocean Operations and Civil Engineering, Faculty of Engineering, Norwegian University of Science and Technology (NTNU).

Dr. Zhang received his Ph.D. degree on Mechanical and Electronic Engineering in 2003. From 2004, he worked as Postdoctoral fellow, senior researcher at the Institute of Technical Aspects of Multimodal Systems (TAMS), Department of Informatics, Faculty of Mathematics, Informatics and Natural Sciences, University of Hamburg, Germany. In Feb. 2011, he finished the Habilitation on Informatics at University of Hamburg. Dr. Zhang joined the NTNU, Norway in April 2011 where he is a Professor on Mechatronics. From 2011 to 2016, Dr. Zhang also hold a Norwegian national GIFT Professorship on product and system design funded by Norwegian Maritime Centre of Expertise. In 2019, Dr. Zhang has been elected to the member of Norwegian Academy of Technological Sciences.

Dr. Zhang has engaged into two main research areas including control, optimization and AI application especially on autonomous vehicle; and marine automation, digitalization and ship intelligence. He has applied for and coordinated more than 30 projects supported by Norwegian Research Council (NFR), German Research Council (DFG), EU, and industry. In these areas, he has published over 200 journal and conference papers as author or co-author. Dr. Zhang has received four best paper awards, and five finalist awards for best conference paper at International conference on Robotics and Automation.