Navigating Patterns Analysis for on-board Guidance Support in Crossing Collision Avoidance Operations

Baiheng Wu, Guoyuan Li *, Luman Zhao, Hans-Ingar Johansen Aandahl, Hans Petter Hildre, and Houxiang Zhang
Department of Ocean Operations and Civil Engineering
Norwegian University of Science and Technology (NTNU)
Ålesund, Norway
{baiheng.wu, guoyuan.li, luman.zhao}@ntnu.no, hiaandah@stud.ntnu.no, {hans.p.hildre, hozh}@ntnu.no

***Abstract*—Proper interpretation and classification of navigators' operational behaviors is crucial to the design of on-board decision support system. This research work dives into the study of navigators' navigating patterns in the maritime collision avoidance traffic situation. Three navigating patterns, specifically conservative, moderate, and aggressive modes, are identified with respect to the collision risk assessment by interpreting data collected from the global positioning system and the automatic identification system. The collision risk assessment is realized following the collision risk modelling concept of the closest point of approach. Then a human-centered on-board guidance support system is developed according to the patterns identified in order to help navigators make decisions. This proposed approach is implemented in the scenario of sailing across a narrow strait, where human intelligence remains necessary in the foreseeable future. The research experiment was conducted on Kongsberg maritime simulators. 36 rounds of sailing data containing 108 collision avoidance sub-tasks were collected and analyzed to classify navigating patterns. Afterwards, a guidance support system was designed based on the patterns' demonstration. An additional experiment to test the developed system in the same scenario was organized on the same simulator. The results show that the system can considerably improve the navigator's navigation management ability in collision avoidance operations. Our approach combines data analysis and risk modelling with authentic human-operated navigating data and traffic information, which makes it distinct from traditional intuitive and cognitive maritime traffic modelling. It is the first one that defines navigating patterns and puts them into potential industrial application pragmatically.**

***Index Terms*—maritime autonomous surface ships (MASS), navigating patterns, risk assessment, decision support, guidance system, collision avoidance**

NOMENCLATURE

AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
CA	Collision Avoidance
CRA	Collision Risk Assessment
COLREGs	Convention on the International Regulations for Preventing Collisions at Sea
CPA	the Closest Point of Approach (except for CPA in Fig. 13 and specific clarification can be found in the caption to Fig. 13)
DCPA	Distance the Closest Point of Approach
ECDIS	Electronic Chart Display and Information System
GPS	Global Positioning System
GNSS	Global Navigation Satellite Systems
GUI	Graphic User Interface
HITL	Human-in-the-Loop
IMO	International Maritime Organization
MASS	Maritime Autonomous Surface Ships
NP	Navigating Pattern
NPA	Navigating Patterns Analysis
OS	Own Ship
TCPA	Time to the Closest Point of Approach
TS	Target Ship

* *corresponding author*

I. INTRODUCTION

Intelligent maritime transportation system (IMTS) has received great attention in both academia and industry in the past decades [1][2]. IMTS is expected to increase maritime transportation efficiency, prevent human-factor related failures, and reduce the cost of human resources [3][4]. With increasing data accessibility, the topic of leveraging data to support IMTS has gained popularity and thus studied and developed extensively [5][6][7]. In current industrial practice, mainstream data sources include global navigation satellite systems (GNSS), automatic identification system (AIS), on-board equipped inertia measurement units (IMU) and gyros, and shore-based traffic and environment sensing infrastructures (including radars, optical/infrared cameras). Data are often re-organized and plotted on on-board graphical interface, such as automatic radar plotting aid (ARPA) and electronic chart display and information system (ECDIS), to efficiently assist navigators. These data and tools, when well managed and interpreted, can potentially optimize navigating solutions to major concerns raised in the field of IMTS, such as ship autonomy, traffic surveillance, route planning, transportation scheduling, and etc.

The development of the ship autonomy for maritime autonomous surface ships (MASS) has been a major topic in IMTS for decades [8]. Under the influence of rapid development of advanced control theory and computer sciences, this topic is now experiencing a rejuvenation, and related research has become increasingly systematic. Different parties, including national/international organizations [9][10], classification societies [11][12], and research entities [13][14], have provided their particular insights of definition and/or interpretation on various levels of MASS. The degrees of MASS

TABLE I
DEGREES OF AUTONOMY FOR MASS OPERATIONS IDENTIFIED BY IMO

Level	Exercise scope
Degree 1	Ship with automated processes and decision support
Degree 2	Remotely controlled ship with seafarers on board
Degree 3	Remotely controlled ship without seafarers on board
Degree 4	Fully autonomous ship

identified by International Maritime Organization (IMO) are listed in Table I [9].

According to Table I, from the manually operated ships to the fully autonomous ships, there are several in-between degrees of the development of ship intelligence. Except for in Degree 4 when humans are out of the loop, human controls at different levels over the ship are yet irreplaceable. Current ship intelligence, which is already implemented in maritime industry, is only at Degree 1 according to IMO. This implies that to reach the excellence of MASS, there is still a long way to go. To do so, we should address human-machine interaction problems as well as the conflicts caused between human knowledge/experience and the developed ship intelligence. In this regard, understanding navigators' behaviors as well as identifying and analyzing their navigating patterns (NP) is indispensable in accelerating the development of MASS [15].

The key issue that hinders IMTS and MASS from being fully realized is that maritime conventions and regulations are predominantly qualitative-based, which lacks quantitative approaches on standardized operational practice. For example, in *the Convention on the International Regulations for Preventing Collisions at Sea* (COLREGs) [16], it only regulates the conditions quantitatively in which ships are deemed to be caught in a collision risk situation, but it does not give any specific standard for operations in a quantitative way to avoid collision [17]. Basically, COLREGs itself is formulated in an intuitive manner as a general guidance for the human-centered on-board control; yet, this has brought two main issues:

- Navigation trainees usually find COLREGs difficult to understand [18]. The decision on the CA operational actions strongly depends on expertise-knowledge.
- A qualitative COLREGs imposes great challenges on the development and implementation of IMTS and MASS, regardless of the rule-based or algorithm-based approach.

However, for airborne crafts in aviation industry where operating environment is also unstructured, a series of quantitative collision avoidance (CA) guidelines has been formulated together with corresponding operation recommendations [19]. Although waterborne sailing is a relatively low-speed and slow-response process, establishing quantitative guidelines is crucial to develop MASS.

In this paper, we narrow down the research scope to the NPs of navigators when sailing in a narrow strait with intense marine traffic coming from the starboard side of the own ship (OS). This scenario is drawn from traffic environment commonly-seen in some busy straits, such as the Dover strait. In these congested waters, there are specific separation schemes to secure the safety and efficiency of the traffic. When a ship is crossing such strait, usually the target ships (TSs) are coming from either the starboard or the portboard side at a time. We summarize navigators' NPs reflected by the recorded maneuvering data and route evaluation in such traffic environment. Then we use the concluded patterns' features to provide on-board guidance in order to support navigators.

The following issues are addressed in our paper:

- a data-based navigating pattern analysis method is conceived for the crossing scenario in the CA task, and three NPs, specifically conservative, moderate and aggressive modes, are concluded and interpreted;
- a guidance support system is developed based on the navigating patterns analysis (NPA) to assist navigators in making decisions on sailing routes and CA strategies selection.

II. RELATED WORK

In this paper, we mainly focused on the NPA, but we also covered two other minor subjects: risk assessment and on-board decision support for the CA.

Different from the research progress of NPA in the maritime field, similar topics regarding driving styles have been studied extensively in the field of automobile for decades. Driving styles under different circumstances have been investigated and assessed from different perspectives. They are often classified according to different driving styles, such as aggressive-moderate-conservative, risky-mild-safe, and etc [20][21][22][23][24]. Similar research interest can also be found in trains operating along railways [25].

Moving back to the maritime field, the research on NPA incorporates with the investigation on human factors. Most of the recent research items are regulated in the framework of human factors analysis and classification system (HFACS) [26][27]. Human factors affecting navigational safety have been studied from an organizational aspect [28][29]. In addition to HFACS framework, the fault tree analysis (FTA) is also used to tackle human-related maritime accidents [30]. The Bayesian topology network is also utilized to assess the human reliability and risk [31].

A shared characteristic is discovered from previous research that more attention is given to the results and the connected individual events/operations. Another group of researchers put efforts on the operational process study. Instead of discussing about the causalities among individual events, they attempt to make a descriptive interpretation over the navigating process. In terms of the research specifically focusing on the NPs and behavioral modelling, progress is also achieved in conceptualization. The idea to quantitatively describe navigators' behaviors and strategies with respect to risk assessment index has been raised early, but lacks of abundant data to demonstrate it comprehensively [32]. In recent years, scholars attempt to define NPs, for example, an intuitively classification of patterns including chancer (eager to take risk), neutral (conservative), and passive (reluctant to take a risk) patterns in terms of the navigators' attitudes towards potential risks [33]; a qualitatively classification including the hazardous and safe patterns summarized from several types of navigators' behavioral profiles (professional, decisive, risk-taker, careful,

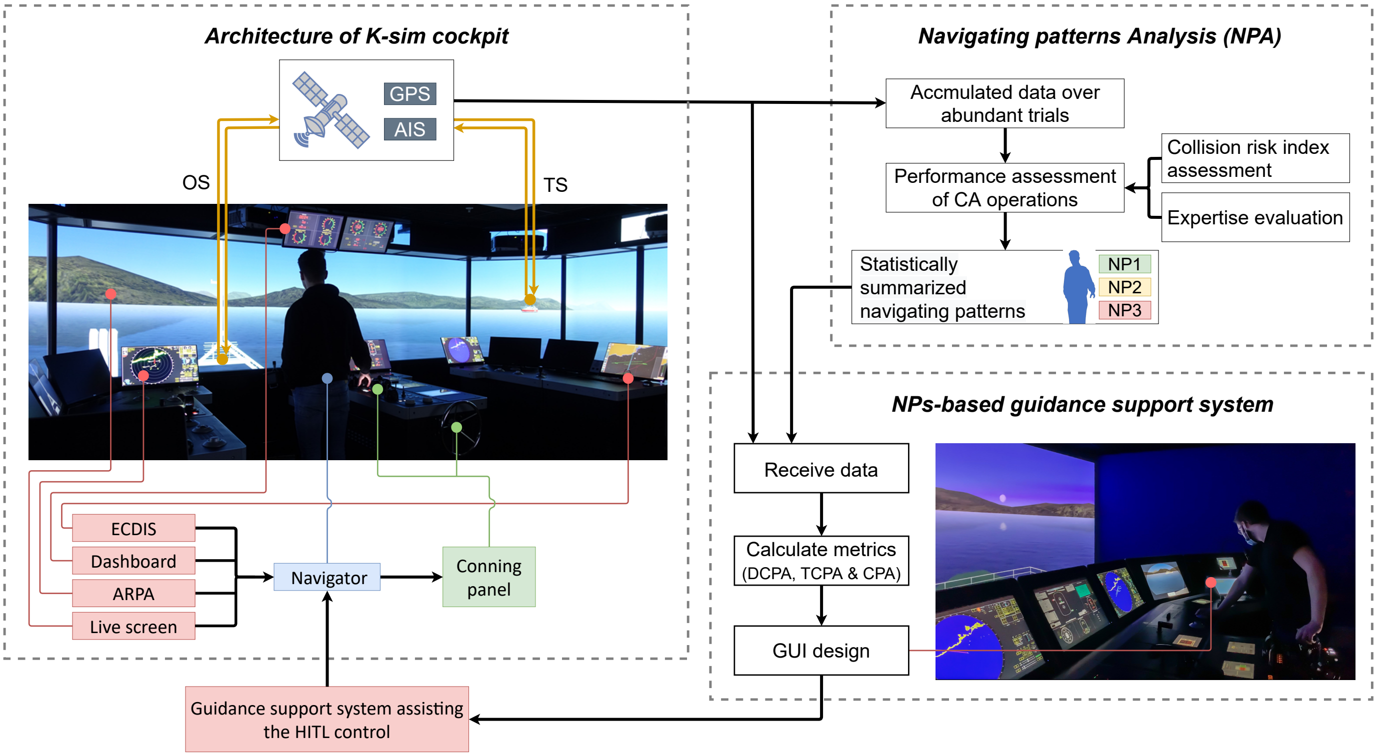


Fig. 1. Workflow of this research work.

and etc) [34]; and a quantitative evaluation over navigators' maneuvering performance level including low-poor, moderate-average, high-excellent, which is realized by analyzing operations' details and ship responses [35].

Different from the automobile field which has readily access to massive road data, maritime practitioners adopt similar strategies as in aviation by using realistic simulator cabins to collect human-centered maneuvering data for training and research purposes [36][37]. Simulator-based data have been used to analyze risk level and human performance in various scenarios [38].

In this research work, we look into the CA operation, which is deemed to be one of the most critical operations during a sailing. Firstly, regarding policy and convention, CA operation is addressed under the COLREGs. As problems in the current COLREGs are already mentioned in Section I, some scholars start to find solutions to quantify the COLREGs [39][40]. Secondly, regarding technological solutions, CA operation can be divided into a sequence of minor tasks, including situation awareness, risk assessment, strategy planning, and control execution [41]. In practice, the first two minor tasks, situation awareness and risk assessment, are usually merged as a complete problem set called the collision risk assessment (CRA). Usually, this CRA is achieved by establishing different models for the collision risk index. Popular metrics used for CRA are distance (between OS and TS) at the closest point of approach (DCPA) and time to the closest point of approach (TCPA) [42]. Aside the metrics, a number of advanced algorithms have been developed for CRA, including the ship domain analysis [43], the concept of the artificial potential field [44], velocity obstacles algorithm [45], and etc. For the CA path planning and control, there are traditional solutions such as the line of sight (LOS) algorithm [46] and other rule-based algorithms [47], while recently as ship intelligence development thrives on machine learning, evolutionary algorithm [48], neural network solution [49] and reinforcement learning algorithm [50] have also been introduced to solve CA problems.

In this paper, we establish the concept of navigating patterns to provide a quantitative guidance solution on the crossing CA operation. We particularly focus on the importance of leveraging expertise wisdom and collect, interpret, and conclude the human navigators' operational data to construct the concept and the derived solution for the guidance support.

III. Methodology

In this section, we introduce the methodology of our research, which includes encounter situation setup, description of the simulator (experiment) environment and data sources, and relevant calculated metrics used in NPA and the design of the guidance support system. The simulator environment is illustrated in Fig. 1, and two important issues, namely the NPA and the design of the guidance support system, are presented in sub-flowcharts in Fig. 1. Details of these two issues are later introduced in Section IV and V.

A. Encounter situation

We investigate the crossing CA operation in a narrow strait as the research object. Three different ship encounter scenarios according to the COLREGs are demonstrated in Fig. 2, among which, our research interest lies in TS_1, where the TS is the stand-on vessel, and the OS must take actions to prevent

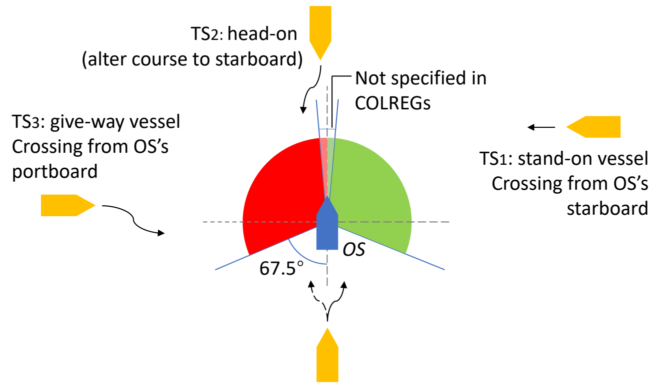


Fig. 2. Three scenarios when OS and TSs are in sight of one another according to COLREGs.

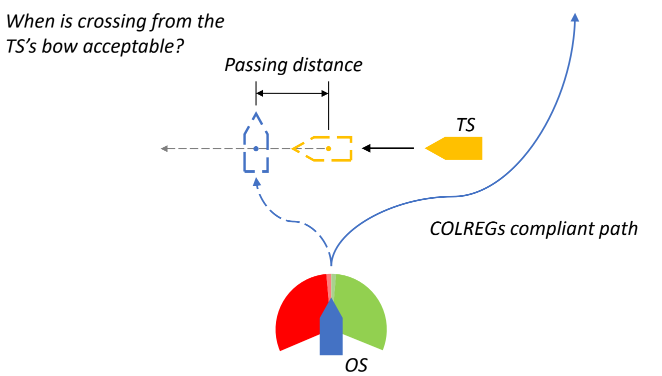


Fig. 3. Path candidates when OS encounters a TS from the starboard side.

potential risks. We adopt this scenario to address the pragmatic industrial engineering problem existed in many heavy-traffic straits at sea.

In Fig. 3, two candidate paths when the OS encounters the TS are shown. According to COLREGs Rule 15 Crossing Situation, the OS should alter its course to the starboard side to make a detour and pass behind the stern of the TS:

> **Rule 15 Crosing Situation** When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

Although COLREGs Rule 15 regulates its preference on who ought to be the stand-on/give-way vessel and on the corresponding operational requirements, it still reserves the possibility to let vessels violate the rule. In addition, from the industrial practice perspective, Rule 15 is deemed to be vague for actual operation. For instance, in busy strait water channels, if the OS sticks to the rule, it is barely possible for them to navigate across the strait when ships are coming from the starboard side in an endless stream.

In this context, we attempt to quantify the metrics that describe a hierarchy of the maneuverable space which enables the OS to pass from the bow of the starboard-side-coming TS, and name them with different NPs.

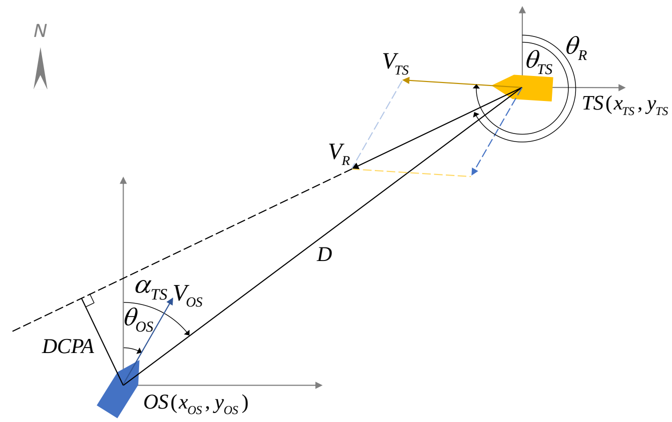


Fig. 4. Illustration of DCPA.

B. Simulator environment

Data used in this section are collected from a Kongsberg K-Sim® maritime simulator, as shown in Fig. 1 - architecture of K-sim cockpit. The simulator system can provide encoded GPS (only OS) and AIS (both OS and TS) data in standard forms starting with \$GP and \$AIVD, and the decoded data selected for the research goal in this section include:

- From GPS: course, speed over ground, latitude and longitude (in WGS84), north and east (in UTM32N);
- From AIS: MMSI (Maritime Mobile Service Identity, a series of nine digits which is used to uniquely identify the ship), latitude and longitude (in WGS84), course.

The positioning difference recorded in different coordinate systems, i.e. WGS84 and UTM32N, can be converted reciprocally. To make the calculation easier, we converted the longitude and latitude in WGS84 to North and East in UTM32N, with the international unit meter.

C. Related metrics

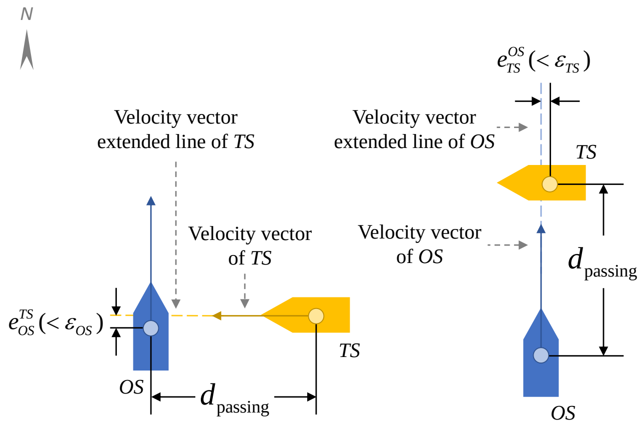
We use one of the most important collision risk index, DCPA, as the main criterion to assess NPs. The DCPA is a synthesis index which is capable to reflect the motion properties of both OS and TS [51]. It is illustrated in Fig. 4, and calculated as:

$$\mathrm{DCPA} = D \cdot \sin(\theta_R - \alpha_{TS}), \tag{1}$$

where D is the distance between OS and TS, θ_R is the course of the relative velocity between OS and TS, and α_{TS} is azimuth angle of TS to the center of OS (irrespective of the course of OS).

Considering the collected data, Eq. 1 can be re-wrote as:

$$\begin{aligned}\mathrm{DCPA} &= D \cdot \sin(\theta_R - \alpha_{TS}) \\ &= D \cdot (\sin\theta_R \cdot \cos\alpha_{TS} - \cos\theta_R \cdot \sin\alpha_{TS}) \\ &= D \cdot (\frac{V_{R,x}}{||V_R||} \cdot \frac{D_y}{D} - \frac{V_{R,y}}{||V_R||} \cdot \frac{D_x}{D}) \\ &= \frac{V_{R,x}}{||V_R||} \cdot D_y - \frac{V_{R,y}}{||V_R||} \cdot D_x,\end{aligned} \tag{2}$$



(a) OS passing from the bow of the TS

(b) TS passing from the bow of the OS

Fig. 5. Illustration the calculation of the passing distance at t_{passing}.

where V_R is the relative velocity between OS and TS. The subscript x, y represent the projected component on the east and north directions.

Since the speed over ground (V_{OS}, V_{TS} for OS and TS respectively) and course angle (θ_{OS}, θ_{TS} for OS and TS respectively) are collected, $V_R(V_{R,x}, V_{R,y})$ can be calculated as:

$$\begin{aligned} V_{R,x} &= V_{TS,x} - V_{OS,x} \\ &= V_{TS}\sin\theta_{TS} - V_{OS}\sin\theta_{OS}, \end{aligned} \tag{3}$$

$$\begin{aligned} V_{R,y} &= V_{TS,y} - V_{OS,y} \\ &= V_{TS}\cos\theta_{TS} - V_{OS}\cos\theta_{OS}. \end{aligned} \tag{4}$$

Based on the positions of OS and TS, $D(D_x, D_y)$ can be calculated as:

$$\begin{aligned} D_x &= x_{TS} - x_{OS}, \\ D_y &= y_{TS} - y_{OS}. \end{aligned} \tag{5}$$

Taking Eq. 3 - 5 into Eq. 2, the DCPA can then be obtained.

In addition to DCPA, the passing distance is calculated for the further interpretation. The passing distance is briefly illustrated as in Fig. 3. Comparing Fig. 4 and 5, we can infer that the concept of the passing distance is more concise for the intuitive comprehension. Different from DCPA which serves as a capable index for collision prediction by exploiting the kinetics information of the OS and TS, the conceptual of the passing distance can be leveraged as an index candidate for the result-oriented assessment. There is not a general definition given to the passing distance, so in this paper it is defined, specifically for the crossing collision avoidance situation, as:

> **Passing Distance:** when two vessels are in a crossing collision avoidance close-encounter situation, the distance when one vessel first pass the velocity vector line of the other from the bow is defined as the passing distance.

According to the definition, passing distance is illustrated as in Fig. 5. It is imperative to figure out the moment t_{passing} when one vessel first pass the other. The offset from OS to the velocity vector of TS, e_{OS}^{TS}, can be calculated as:

$$\begin{aligned} \hat{y}_{OS} &= x_{OS} \cdot \cot\theta_{TS} + (y_{TS} - x_{TS} \cdot \cot\theta_{TS}), \\ e_{OS}^{TS} &= |(\hat{y}_{OS} - y_{OS}) \cdot \cos\theta_{TS}|; \end{aligned} \tag{6}$$

while the offset from TS to the velocity vector of OS, e_{TS}^{OS}, can be calculated as:

$$\begin{aligned} \hat{y}_{TS} &= x_{TS} \cdot \cot\theta_{OS} + (y_{OS} - x_{OS} \cdot \cot\theta_{OS}), \\ e_{TS}^{OS} &= |(\hat{y}_{TS} - y_{TS}) \cdot \cos\theta_{OS}|. \end{aligned} \tag{7}$$

Since x_{OS} and x_{TS} can be regarded as functions of time t, the passing moment t_{passing} can be calculated as:

$$\min t_{\text{passing}}, \text{ s.t. } e_{OS}^{TS} < \varepsilon_{OS} \text{ or } e_{TS}^{OS} < \varepsilon_{TS}, \tag{8}$$

where ε_{OS} and ε_{TS} are small values and shall be determine according to the vessels' velocities and the sampling frequencies in practice. And the distance between the OS and TS at t_{passing} is denoted as passing distance d_{passing}.

To design a guidance support system, in addition to the DCPA and passing distance, we calculated another two items, time to the closest point of approach (TCPA) and the coordinates of CPA for the corresponding TSs.

TCPA is calculate as:

$$\begin{aligned} \text{TCPA} &= D \cdot \frac{\cos(\theta_R - \alpha_{TS})}{||V_R||} \\ &= D \cdot \frac{(\cos\theta_R \cdot \cos\alpha_{TS} + \sin\theta_R \cdot \sin\alpha_{TS})}{||V_R||} \\ &= \frac{(\frac{V_{R,y}}{||V_R||} \cdot D_y + \frac{V_{R,x}}{||V_R||} \cdot D_x)}{||V_R||}, \end{aligned} \tag{9}$$

The coordinate of the CPA$(x_{\text{CPA}}, y_{\text{CPA}})$ is calculated as:

$$\begin{aligned} x_{\text{CPA}} &= x_{OS} + \text{TCPA} \cdot V_{OS,x}, \\ y_{\text{CPA}} &= y_{OS} + \text{TCPA} \cdot V_{OS,y}. \end{aligned} \tag{10}$$

IV. Experiment I: Navigating patterns analysis

In this experiment, we deal with problems of how NPs can be conceptualized by collectable data. In general, we attempt to seek the navigators' maneuvering logic and laws that are concealed in the data, and conclude different NPs. The significance of this section lies in two aspects: improving on-board decision support for the HITL-level MASS from an expertise perspective, and developing ship intelligence by rationalizing the use of data, for instance how they should be labelled.

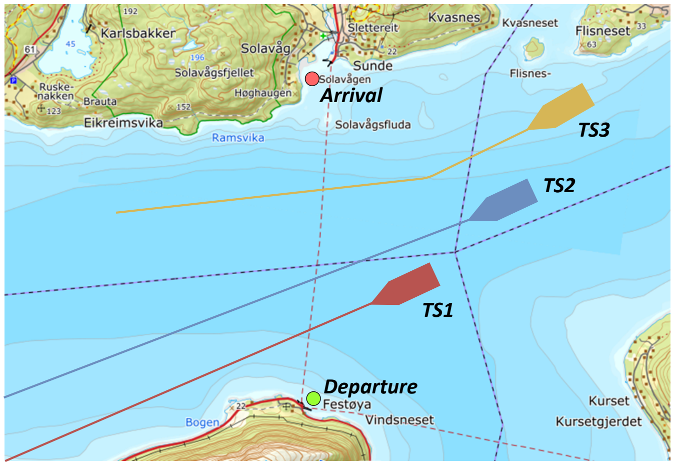


Fig. 6. Scenario layout of the experimental CA sailing.

TABLE II
SHIP INFORMATION AND EXPERIMENTAL CONDITIONS SETUP

Property	OS	TS1	TS2	TS3
Basic information about ships				
length (m)	88	133	165	170
beam (m)	13.8	19.4	27.1	27.5
Initial states				
heading (°)	312	245	245	240
latitude (°)	62.3802	62.3882	62.3986	62.4031
longitude (°)	6.3328	6.3357	6.3569	6.3443
speed (knots)	0	14	15	10

A. Experiment setup and implementation

The water channel between two ports Solavågen and Festøya in Ålesund area of Norway is selected as the basis for the simulation scene. The TSs in the simulation are named as TS1, TS2 and TS3, and all of them come from the starboard side of the OS. The scenario construction is sketched in Fig. 6. Therefore, the simulator-based sailing task for the OS can be regarded as a complete sailing task comprised by three sub-CA tasks with different encounter details as shown in Table II. The experiment implementation is carried out on K-sim® simulators at NTNU, NMK (Norwegian Maritime Competence Center) in Ålesund. We collected 36 trial sailings in total, and the trials are labelled in the form 'F_R_B_' ('_' is a digit), where F means the experiments take place in February, while the digit following F represents the date; R is abbreviated for round, and the digit following R represents the round number; and B is abbreviated for bridge, and the digit following B represents the bridge serial number. For example, F4R2B2 means the trial takes places on February 4th, in round 2, and on the bridge No. 2.

B. Pattern analysis

In this part, we will inspect and visualize the collected data, discuss the performance in each trial and how the collision risk index reflects the risk awareness with respect to the expertise perspective, and attempt to setup the clues that can sketch navigating patterns.

1) CA navigating schemes: In the 36 trials, navigators take 5 different CA navigating schemes when they managed to complete the trial with multiple TSs. Passing from the bow of the TS is denoted as B, while passing from the stern of the TS is denoted as S. Then the 5 schemes are S-B-B, S-S-S, S-S-B, B-S-S, and B-B-B, and they appears in 19, 11, 3, 1, and 2 trials (out of 36 trials) respectively. Theoretically, there can be another three schemes, including B-B-S, B-S-B, and S-B-S, but navigators do not select to complete the task in these schemes. It is inferred that these schemes lead to odd paths that are neither efficient nor safe. The trial F4R2B2 with the scheme S-S-S is plotted in Fig. 7. In the chart, the footprints of six moments are detached. A vector line starting from the center of the OS with three markers indicates the predicted position in 1, 2, and 3 minutes in the current course direction. Each sub-CA task with respect to each TS are corresponding to 2 footprints, 1 and 2 for TS1, 3 and 5 for TS2, and 4 and 6 for TS3. The first footprint of each sub-CA task points to the moment when the OS/TS passes the velocity vector of the TS/OS, i.e. the moment of passing (the moment when the passing distance is achieved). While the second footprint of each points to the moment when the OS arrives the CPA. So Fig. 7 demonstrates the detail of the trial that:

- At 2:09, TS1 passes the velocity vector of the OS;
- At 2:43, OS arrives the CPA w.r.t. TS1;
- At 3:00, TS2 passes the velocity vector of the OS;
- At 4:02, TS3 passes the velocity vector of the OS;
- At 4:33, OS arrives the CPA w.r.t. TS2;
- At 7:18, OS arrives the CPA w.r.t. TS3;

It is interesting to find that TS3 passes the OS before the OS arrives the CPA with TS2. This is due to the definition of passing distance, since the passing is deemed to happen and get over as long as one vessel passes the velocity vector of the other. Therefore, although OS is far from reaching TS3 at 4:02, due to the course alternation operation on the OS, TS3 passes the OS passively. Nevertheless, we cannot conclude the CA sub-task w.r.t. is over. Since as the OS restores its course to the direction of the destination, the collision risk may be arisen again. While in situation, although the collision risk may reemerge, there is a low possibility for a collision to happen. In this scenario where the TS has passed the OS, navigators usually chase the stern of the TS instead of immediately altering the course heading to the destination, and will steadily alter the course directing to the destination after the collision risk is totally revoked.

The DCPA and passing distance w.r.t. the three TSs in F4R2B2 is shown in Fig. 8. It shows a fact that the passing moment under the passing distance definition (in Fig. 5) can happen at very early stage, even when the OS is still far away from the TS. From the human perspective, when navigators see the TS have passed the OS from the course direction, they have a sense of low collision risk.

2) Expert evaluation: The 36 trials, which includes 108 sub-CA tasks in total, are evaluated by experienced navigators rather than the navigators themselves. Three different evaluation levels are established to rate the CA performance. During evaluation, the three levels labelled with green, yellow, and red colors, were used to mark the CA performance, as no

TABLE III
EXPERT EVALUATION ON EACH CA AND ITS INFO

	Trial No.	TS1 Evl.	TS1 DCPA (NM)	TS1 $d_{passing}$ (NM)	TS2 Evl.	TS2 DCPA (NM)	TS2 $d_{passing}$ (NM)	TS3 Evl.	TS3 DCPA (NM)	TS3 $d_{passing}$ (NM)	$d_{OS}^{arrival}$ (NM)
S-B-B*											
1	F4R3B1		0.211	0.266		0.221	0.318		0.270	0.409	0.642
2	F4R3B2		0.181	0.235		0.251	0.396		0.403	0.612	0.583
3	F4R4B2		0.161	0.222		0.321	0.413		0.533	0.626	0.403
4	F5R1B4		0.175	0.252		0.265	0.367		0.529	0.619	0.352
5	F5R2B2		0.159	0.266		0.251	0.358		0.456	0.585	0.251
6	F5R3B2		0.149	0.256		0.341	0.441		0.536	0.638	0.346
7	F5R3B4		0.164	0.241		0.256	0.346		0.553	0.632	0.374
8	F5R4B2		0.151	0.250		0.331	0.411		0.513	0.634	0.298
9	F5R4B4		0.195	0.290		0.246	0.331		0.547	0.614	0.390
10	F4R4B1		0.174	0.224		0.245	0.356		0.379	0.520	0.528
11	F5R1B3		0.155	0.231		0.265	0.371		0.351	0.526	0.327
12	F5R2B1		0.183	0.231		0.206	0.281		0.249	0.352	0.568
13	F5R3B1		0.176	0.219		0.221	0.327		0.219	0.322	0.621
14	F5R4B3		0.131	0.201		0.222	0.343		0.349	0.459	0.231
15	F4R4B3		0.237	0.280		0.179	0.226		0.308	0.400	0.673
16	F4R2B1		0.202	0.252		0.161	0.258		0.221	0.316	0.624
17	F4R5B3		0.162	0.274		0.151	0.220		0.351	0.440	0.193
18	F4R5B4		0.112	0.181		0.201	0.340		0.321	0.428	0.173
19	F5R2B3		0.119	0.195		0.191	0.322		0.386	0.487	0.324
S-S-S											
20	F4R2B2		0.290	0.329		0.290	0.795		0.290	1.165	0.618
21	F5R2B4		0.322	0.351		0.292	0.712		0.308	0.951	0.684
22	F5R3B3		0.282	0.340		0.342	0.823		0.208	1.110	0.473
23	F5R1B2		0.222	0.334		0.142	0.343		0.308	0.323	1.158
24	F4R5B2		0.192	0.290		0.172	0.346		0.278	0.556	0.839
25	F5R1B1		0.287	0.326		0.176	0.256		0.141	0.220	0.857
26	F4R3B4		0.292	0.355		0.150	0.263		0.171	0.296	0.743
27	F4R2B3		0.190	0.262		0.190	0.501		0.200	0.704	0.598
28	F5R4B1		0.237	0.300		0.099	0.168		0.118	0.231	0.737
29	F4R5B1		0.222	0.281		0.088	0.145		0.090	0.140	0.734
30	F4R3B3		0.202	0.277		0.080	0.158		0.091	0.181	0.730
S-S-B											
31	F4R1B1		0.175	0.217		0.146	0.234		0.300	0.411	0.747
32	F4R1B4		0.070	0.125		0.111	0.172		0.428	0.519	0.623
33	F4R4B4		0.152	0.250		0.110	0.382		0.171	0.194	0.401
B-S-S											
34	F4R2B4		0.180	0.220		0.040	0.044		0.152	0.313	1.038
B-B-B											
35	F4R1B2		0.180	0.241		0.291	0.588		0.700	1.002	0.398
36	F4R1B3		0.120	0.185		0.301	0.502		0.650	0.920	0.310

* *Note:* *S denotes for passing from the Stern of the TS;*
B denotes for passing from the Bow of the TS.

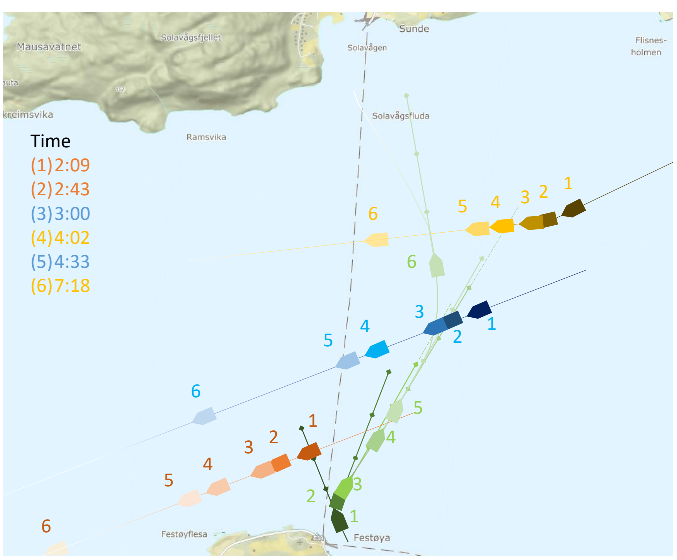


Fig. 7. An example of sea chart (trial F4R2B2, CA scheme: S-S-S).

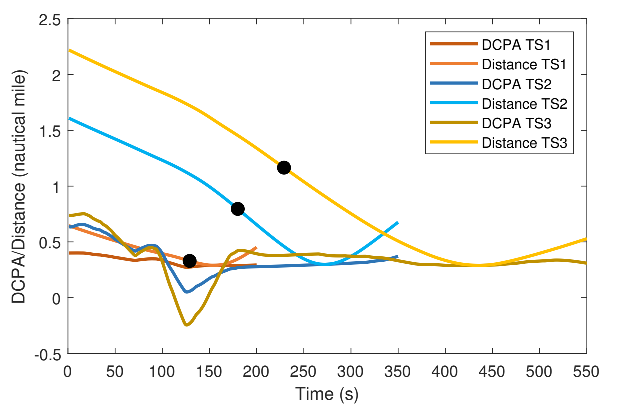


Fig. 8. DCPA and distance to different TSs of the sea trial F4R2B2 in Fig. 7. The black dots on curves of Distance TS_ represents data points at the passing moments.

specific terminology was yet created. According to navigators, the different evaluation levels can be intuitively described as:

- **green** means the OS is operated to pass the TS at an ample distance; if passing from the bow, this distance enables the stand-on vessel to actively take action to avoid CA in some emergencies (such as OS engine failure). Meanwhile, passing in this level usually requires sparse operations on the OS control;

- **yellow** means the OS is operated to pass the TS at a sufficient distance with a certain degree of critical operations.
- **red** means the OS is operated to pass the TS at a tight distance, and the navigator needs to maneuver the vessel meticulously to safely pass the TS. If passing from the bow, sometimes such pattern may provoke the operators of the TS.

The evaluation results are listed in Table III. It shows that a navigator may change his navigating strategies (the evaluation colors) in different sub-tasks.

- In CA with TS1, the OS passes TS1 from the bow only in 3 trials, and all of them are rated as red. In this task, the velocity of the OS has not been developed. Its initial course is in accordance with the quay infrastructure, this also decreases the maneuvering feasibility of the OS at the beginning stage. In this case, passing from the bow of TS1 becomes an adventurous strategy.
- In CA with TS2, the OS passes TS2 from the bow in 21 trials, and from the stern in 15 trials. None of the 21 trials passing from the bow in this sub-task is rated with the green label, while 5 trials taking the S-B-B CA scheme are rated with the red label. Passing TS1 from the stern detains the navigator to alter the course of the OS in the direction of passing TS2 from the bow. While in the 15 trials passing from the stern of TS2, 3 are rated as green, 8 are rated as yellow, and 4 are rated as red. For the 3 green trials, they are rated as green in the CA with TS1 as well. For the 4 red trials, their DCPA in the preceding sub-task are also at a low level in comparison with trials 20-27 and 31-33. However, it can be inferred that navigators are more flexible to choose the strategy when operating the OS to pass from the stern of the TS.
- In CA with TS3, the OS passes TS3 from the bow in 24 trials, and from the stern in 12 trials. When passing from the bow, 11 trials are rated as green, 11 as yellow, and 2 as red; when passing from the stern, 6 trials are rated as green, 5 as yellow, and 1 as red. The evaluation distribution in two passing strategies are similar. The 2 red cases in which the OS passes from the stern reveals a strong peculiarity on navigating patterns of navigators, since in the preceding sub-task they also chose to pass from the stern of the TS tightly.

In accordance with the expertise evaluation results, and their assessment principles, we renamed the color schemes with the terminology of the navigating patterns: the green, yellow, and red colors stand for conservative, moderate, and aggressive modes respectively.

3) DCPA features: As the terminology of navigating patterns, including conservative, moderate, and aggressive, are proposed, we consequently investigate the mapping between the patterns and the metrics (DCPA and passing distance).

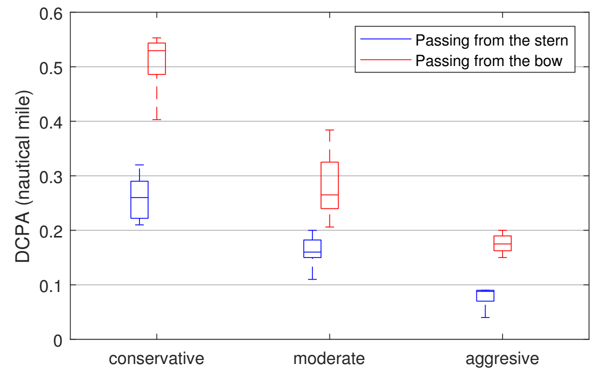


Fig. 9. Distribution of DCPA in terms of different navigating patterns.

TABLE IV
MEAN DCPA FOR CA WITH DIFFERENT TSS

Passing from	TS1	TS2	TS3
Stern	0.191	0.161	0.197
Bow	0.160	0.242	0.405

*The unit of values is nautical miles.

Fig. 9 depicts the DCPA distribution in terms of different navigating patterns when passing from the stern and the bow separately. In the conservative pattern, passing from the stern and the bow has their medians around 0.289 and 0.533, and the distributed intervals (0.210, 0.340), (0.403, 0.553); in the moderate pattern, the medians are 0.160 and 0.268, and the intervals are (0.110, 0.202), (0.206, 0.386); in the aggressive pattern, the medians are 0.088 and 0.175, and the intervals are (0.040, 0.099), (0.120, 0.201).

From the distribution and the featured indexes, two facts can be found:

- The DCPA values selected by navigators to maneuver the OS at are distinctly different between passing from the stern and from the bow, regardless of the navigating patterns. From the collected data, the median of DCPA values for passing from the bow are 1.84, 1.68, and 1.99 times as for passing from the stern in the conservative, moderate, and aggressive pattern separately; the minimum are 1.92, 1.87, and 3.00 times; the maximum are 1.62, 1.91, and 2.03 times.
- The DCPA values between different patterns are clearly scattered on different scales, i.e. the DCPA can reveal the navigating patterns to a certain extent.

Table IV gives the mean DCPA values of passing from the stern/bow in each sub-tasks. It shows that DCPA is less influenced by the CA-scenario difference in encounters with different TSs when passing from the stern, while the mean DCPA inclines to be larger when passing from the bow than from the stern. When passing from the stern, navigators prefer keeping the vessel to the original sailing route (without TSs on the route) as close as possible to achieve the least deviation and detour from the original route. To realize it, navigators usually keep a moderate speed to the course direction pointing to the stern of the TS. And once the TS passes, navigators

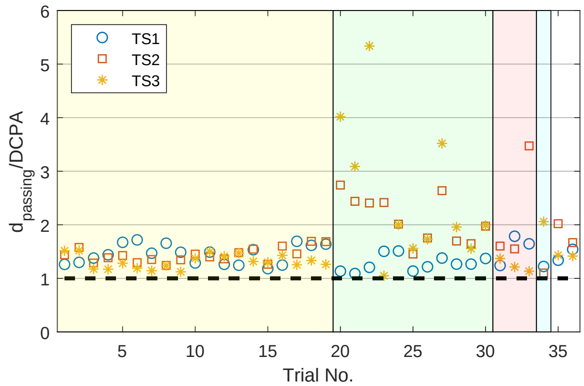


Fig. 10. Plot of d_{passing}/DCPA values. 5 invernals on x-axe are S-B-B, S-S-S, S-S-B, B-S-S, and B-B-B. They are painted with distinguishable background colors.

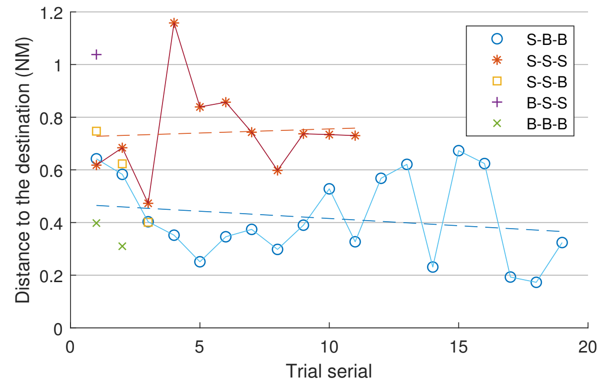


Fig. 11. Distance to the destination at T=550 s. The dash lines in red and blue are trendlines of datasets S-S-S and S-B-B.

alter the course back to the stern of the next TS, or directly to the destination (if no more CA operation needed for another TS). This results in the insignificant difference in mean DCPA values between CA tasks with different TSs. When passing from the bow, the OS speed varies when encounters different TSs. When encounters TS1, the OS speed is low and developing; when encounters TS2, it is moderate and still developing; when encounters TS3, it is fully developed. It can be inferred that navigators choose to operate the OS at a larger DCPA to reduce the risk caused by the high-speed passing from the bow of the TS.

4) Passing distance $d_{passing}$: Based on data in Table III, we calculate d_{passing}/DCPA values accordingly, and results are plotted as in Fig. 10. The x-axe is divided into 5 intervals in terms of navigating schemes (see in Table III). The most important fact concluded from Fig. 10 is that all values are greater than 1, i.e. d_{passing} is always greater than the DCPA. From the definition of d_{passing} we know that it is strict the distance when one ship passes the center line (extended) of another. d_{passing}/DCPA greater than 1 means the strict passing distance is always larger than the principal metric DCPA. This guarantees the DCPA to be eligible as the collision risk assessment candidate for designing a guidance support system in the further step, which means as long as DCPA is selected in a proper way, d_{passing} is secured.

5) Distance to the destination $d_{OS}^{arrival}$: In order to investigate the efficiency of different CA schemes and navigating patterns, the distance to the destination at T = 550 s is calculated and given in Table III, and is depicted in Fig. 11. Considering the OS has finished the CA sub-tasks with all the three TSs before T = 550 s in all trials, it is a proper time for efficiency assessment.

In terms of different CA scheme, most trial select S-B-B or S-S-S as the CA scheme, and other types are so rarely selected that they are not discussed statistically in this part. From the figure, it shows that the distance to the destination is farther in general when the S-S-S scheme is taken. The S-S-S scheme means that the OS operated strictly under the CA operational requirements according to the COLREGs, while the S-B-B scheme means that the OS only follows the COLREGs in the first CA sub-task, and violates the COLREGs in the rest two sub-tasks. It can be inferred that the violation of the COLREGs is at the aim of increasing the sailing efficiency. This is a balanced decision made by the navigator between the efficiency and the safety.

However, violating COLREGs makes maneuvering demanding for navigators. Comparing Trial No. 16-18, though their strategies seem to be similar according to the classified patterns, the real situation might be contrary. Choosing S-B-B scheme requires navigators to take proper maneuvering commands at very appropriate moments: passing the TS1 from the stern at a ample but close distance, and then alter the heading to pass the TS2 from the bow once the collision risk with TS1 is cancelled. If the navigator does not alter the heading at the correct time, it might be caught in a situation of parallel racing with TS2 to pass from its bow. This may result in a long distance detour from the designed route as Trial No. 15 and 16. To conclude, if navigators take very proper operations at correct time, taking an aggressive strategy may shorten the sailing time (as in No. 17 and 18), but if proper operations are not taken at right time, the endeavor might be in vain.

From the statistics, in Table III, the trials are listed in an order based on the navigating patterns from safe to risky in each scheme. Nonetheless, from the curves in Fig. 11, we cannot find a trend of how the efficiency can be affected by the navigating patterns, which also proves maneuvering the OS in a risky manner may be in vain in increasing the sailing safety.

C. Summary

In this section, we collect and analyze data from a one-direction multi-TSs CA scenario which imitates the traffic separation scheme in the Dover Strait water channel. Based on the calculation of key metrics DCPA and the expertise evaluation upon scenario reconstruction, we concluded three different navigating patterns in terms of the DCPA for passing the TS from the stern and the bow separately. In addition to the DCPA, we use two additional calculated figures, the passing distance and the distance to the destination (at T = 550 s), to comprehensively interpret navigators' rationality in

TABLE V
DCPA SCALES OF DIFFERENT NAVIGATING PATTERNS

Passing from	Aggressive	Moderate	Conservative
Stern	< 0.100	$[0.100, 0.200)$	≥ 0.200
Bow	< 0.200	$[0.200, 0.400)$	≥ 0.400

*The unit of values is nautical miles.

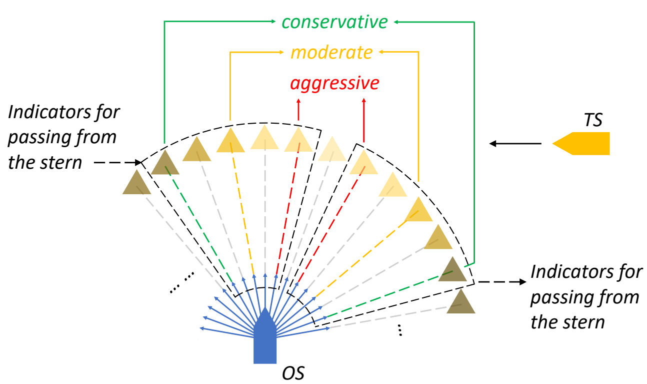


Fig. 12. Illustration of the GUI of the developed system.

CA operations. Finally we concluded the DCPA scales for the different patterns:

Another important factor drawn from the collected data is that there is no evidence for any relationship between sailing efficiency and the navigating patterns in a complete sailing. But the CA scheme, i.e. the path routing, has a significant effect on the efficiency. Such that, a conclusion on navigating patterns will support navigators in regulating ship maneuvering and enhancing their judgement on path routing. Understanding navigating patterns helps to reduce possibility of entering a collision risky zone. It also prevents the OS from deviating far from the original route.

V. Experiment II: Guidance Support System Testing

In this section, we developed a real-time on-board decision support system for human-centered navigation based on the NPA results from Section IV. The aims of developing such a system are:

- for on-board decision support, especially in the seafarers' training program as it has been reported that students in the nautical training think the COLREGs difficult to understand [18], as it is stated in Section IV-C that understanding the NPA can potentially enhance navigators' judgement on path routing;
- for the development of ship intelligence in the framework of MASS shown in Table I, specifically for MASS at human-in-the-loop level. In the current ECDIS and ARPA system, there is very limited information about planning and prediction, which means navigators needs to calculate alternatives and deploy navigation strategies by himself. The system developed in this section offers an innovative supplementary solution to the ECDIS in this respect.

A. Description of the guidance support system

The guidance support system is developed in order to support navigators in making decisions in the CA scenario.

TABLE VI
TEST RESULTS WITH THE DEVELOPED SYSTEM

Trial No.	TS1		TS2		TS3		d_{OS}^{arrival}
	NP	DCPA	NP	DCPA	NP	DCPA	
S-B-B							
MR1		0.142		0.285		0.297	0.517
MR2		0.133		0.237		0.281	0.345
S-S-S							
MR3		0.239		0.146		0.117	0.574
B-B-B							
MR4		0.203		0.328		0.394	0.494

*The unit of values is nautical miles.

Similar as the existing ECDIS, the system to be developed should be concise, informative, and functional. To be concise, it requires that no irrelevant information are shown on the graphic user interface (GUI), which helps navigators focus on key elements. To be informative, it requires the GUI to provide as much information as possible in a wise manner. To be functional, it requires the system can be easily understood for decision making and operation reacting at navigators' favors.

Taking the calculated items as the basis, a GUI of the navigating support system is developed and illustrated in Fig. 12. The step to form this GUI is:

- the DCPA at the current position and speed is calculated, but with different courses. The range of the course is afore the center of the OS (-90°, 90°), and the step is 1°.
- Among the calculated DCPA, the ones with smallest offsets with the values of the navigating patterns are selected to be the indicators for the course in the GUI. And the course lines with red, yellow, and green indicate aggressive, moderate, and conservative navigating patterns accordingly. The raw calculated DCPA values can be either positive or negative, with the positive implying that the OS passes the TS from the bow, and the negative implying the OS passes the TS from the stern. Therefore, it is easy to distinguish these two navigating patterns in terms of passing from the stern/bow when sketching the GUI.
- For the rest calculated DCPA, the TCPA and CPA are calculated at a step of 5°, and the CPA are then drawn on the GUI with triangles in different color depths. The OS tends to encounter a more dangerous situation if it is navigated in the direction of a lighter colored triangle.

The developed system is updated once new AIS/GPS data from the OS and the TSs are received.

B. Validation on simulator and statistical analysis

The developed system is validated in 4 trials in the same scenario as in Section III on the simulator. Among these trials, S-B-B CA scheme is taken in 2 trials, S-S-S and B-B-B CA scheme is taken in 1 trial for each.

The key features of the testing trials are listed in Table VI. Regarding the navigating pattern selection, it can be found that with the developed system, in all four trials, the OS is navigated to pass the TS in the moderate pattern in 15 subtasks, and 1 in the conservative pattern (according to its DCPA, and the definition given in Section IV). We may conclude the system has a positive performance in assisting the navigator to take a moderate pattern to navigate the OS. With respect of the distance to the destination, the performance in S-B-B CA scheme trials (MR1-2) is at an average level compared with trials in Table III; in the trial (MR3) taking S-S-S scheme, it is at a low level, which means the efficiency is high; and in the trial (MR4) taking B-B-B scheme trial, it is higher than trials in Table III. Comparing MR4 with trials F4R1B2-3 in Table III, the NP when passing TS1 is changed from aggressive to moderate, it can be deemed as a result of balancing efficiency and safety.

C. Illustration of an example case

In this part, we take the trial MR2 as an example to see how the developed guidance support system can assist the navigator to take preventive actions in CA operations. We took 3 screenshots from the GUI of the guidance support system during the trial, and the screenshots of the OS at this moment are deemed to be critical for CA operations. They are illustrated in Fig. 13, and the exact times and descriptions of each moment are given in the sub-captions.

In Fig. 13(a), the OS has finished the CA operation with TS1, and it shows that the OS is navigated in a direction between the red and yellow lines which represent aggressive and moderate patterns. Comparing with Fig. 13(b), it can be found the navigator keeps the direction unaltered since the moment in 13(a). At last, the OS passes the TS2 with a DCPA at 0.237 NM in a moderate pattern according to Table V.

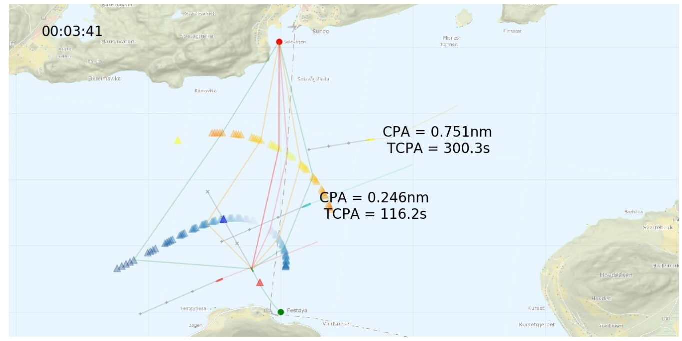
After the OS finishes the CA operation against the TS2, the navigator starts to alter the course. Fig. 13(c) shows that the OS passes over the CA with TS2, and begins to make a back-turn towards the destination. At this moment, the guidance support system shows that if the OS keeps the current course, it will pass the TS3 in a conservative pattern. However, the navigator plans to balance the efficiency under the instruction of the system, so that the navigator gradually alters the course, until the moment in Fig. 13(d), the OS has been switched in a direction identified as moderate. Comparing Fig. 13(c) and 13(d), it is clear that the sailing efficiency is promoted. Furthermore, since the support system suggests that the direction in Fig. 13(d) is moderate, the navigator does not need to worry about any collision risk in this case.

D. Summary

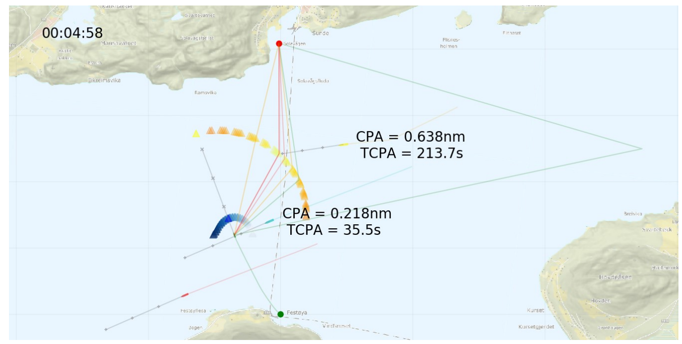
From the statistical analysis and the realization of an example, we conclude that the developed system has a positive influence on navigators' navigating manners. It reduces the navigators' brainwork on calculation and plan of the sailing route to some extent by providing some indicating information.

VI. Limitations and Future Work

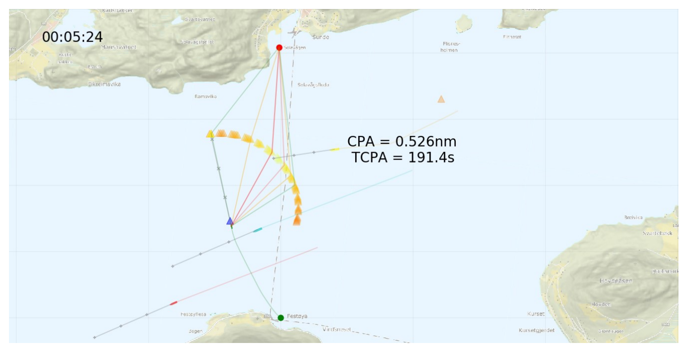
Study on navigator's operational behaviors is essential for the development of MASS. This research work makes an attempt to describe it with the concept of NP and NPA, and the concept is established in a quantitative approach in terms of collision risk index DCPA. The limitation of this research



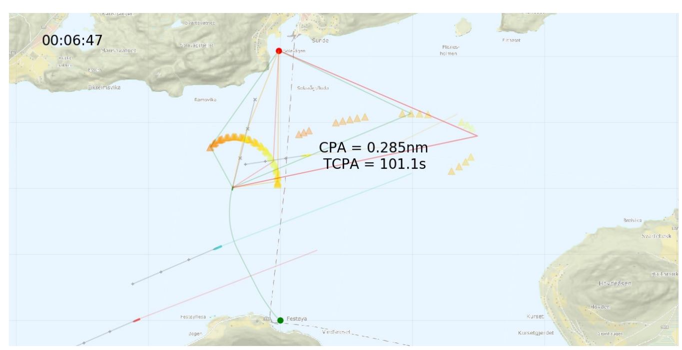
(a) Time 00:03:41, CA with TS1 finished; CA with TS2 undergoing.



(b) Time 00:04:58, OS is passing the velocity vector extended line of TS2.



(c) Time 00:05:24, CA with TS2 finished; CA with TS3 undergoing.



(d) Time 00:06:47, CA with TS3 undergoing.

Fig. 13. Screenshots of the guidance support system for some critical moments from the trial MR2. (The text indicator CPA in this figure represent DCPA, while this is to keep in accordance with the ARPA system and the navigators' conventions. TCPA remains its denotation.)

mainly include: the metrics for NPA only relies on the collision risk index, which may not complete describe navigators' behavioral profiles; the scenario setup only considers the crossing collision avoidance situation.

In the next stage, we will strive on this two aspects. The first one is to establish a complete monitoring system, and take more potential and influential factors into account, such as, brain electrical activities [52][53] and eye movement [54] which may reflect navigators' attention, so that we can obtain a sketch of their navigating patterns with extended details. The second aspect is to collect more data in different scenarios, including other CA situations, as well as other critical ship maneuvering scenarios such as docking. All the planned work is to better understand the navigating logic of human navigators in hope to shed light on both the development of MASS and human-machine interaction performance as the MASS is still at the HITL level.

VII. Conclusion

In this paper, we aimed to solve pragmatic industrial issues of maritime traffic that are often found in narrow water channels. We proposed and conceptualized navigating patterns of navigators, and designed a scenario that imitates the traffic situation as an attempt to find the best navigation solution. Through simulator-based experiments, we collected 36 trials' data for analyzing navigating patterns. Three navigating patterns, namely aggressive, moderate, and conservative modes, were classified with the help of expertise knowledge from experienced navigators. They are further quantified for collision avoidance tasks in terms of the DCPA, an imperative collision risk index. Based on detected navigating patterns, a guidance support system with GUI was developed for the one-direction multi-ship collision avoidance scenario. The developed system was also tested on the simulator, and its performance on guidance support was assessed to be positive from test results. The research approach used in this paper is the first one that conceptualizes and quantifies navigating patterns and subsequently develops their importance on industrial applications in the maritime industry.

Acknowledgement

The research is supported in part by the MAROFF KPN project "Digital Twins for Vessel Life Cycle Service" (Project no.: 280703), and in part by the IKTPLUSS Project "Remote Control Centre for Autonomous Ship Support" (Project nr: 309323) in Norway. The authors extend their gratitudes to Knut Remøy for his help in organizing experiments.

References

[1] Z. Pietrzykowski, "Maritime intelligent transport systems," in *International Conference on Transport Systems Telematics*. Springer, 2010, pp. 455–462.

[2] L. Chen, R. R. Negenborn, Y. Huang, and H. Hopman, "Survey on cooperative control for waterborne transport," *IEEE Intelligent Transportation Systems Magazine*, 2020.

[3] K. Wróbel, J. Montewka, and P. Kujala, "Towards the assessment of potential impact of unmanned vessels on maritime transportation safety," *Reliability Engineering & System Safety*, vol. 165, pp. 155–169, 2017.

[4] S. Fang, Y. Wang, B. Gou, and Y. Xu, "Toward future green maritime transportation: An overview of seaport microgrids and all-electric ships," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 1, pp. 207–219, 2019.

[5] E. Tu, G. Zhang, L. Rachmawati, E. Rajabally, and G.-B. Huang, "Exploiting ais data for intelligent maritime navigation: A comprehensive survey from data to methodology," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 5, pp. 1559–1582, 2017.

[6] R. Skulstad, G. Li, T. I. Fossen, B. Vik, and H. Zhang, "Dead reckoning of dynamically positioned ships: Using an efficient recurrent neural network," *IEEE Robotics & Automation Magazine*, vol. 26, no. 3, pp. 39–51, 2019.

[7] M. Zhu, W. Sun, A. Hahn, Y. Wen, C. Xiao, and W. Tao, "Adaptive modeling of maritime autonomous surface ships with uncertainty using a weighted ls-svr robust to outliers," *Ocean Engineering*, vol. 200, p. 107053, 2020.

[8] Z. Liu, Y. Zhang, X. Yu, and C. Yuan, "Unmanned surface vehicles: An overview of developments and challenges," *Annual Reviews in Control*, vol. 41, pp. 71–93, 2016.

[9] "Regulatory scoping exercise on maritime autonomous surface ships," in *Maritime Safety Committee, 100th session*. International Maritime Organization, 2018.

[10] "Maritime autonomous surface ships industry conduct principles & code of practice, a voluntary code, version 4." Maritime UK, 2020.

[11] "*DNVGL-CG-0264* class guideline: Autonomous and remotely operated ships," *DNVGL*, 2018.

[12] "*LR* code for unmanned marine systems," in *ShipRight Design and Construction, Additional Design Procedures*. Lloyd's Register, 2017.

[13] Ø. J. Rødseth and H. Nordahl, "Definitions for autonomous merchant ships," in *Norwegian Forum for Unmanned Ships, Version*, vol. 1, 2017, pp. 2017–10.

[14] F. Goerlandt, "Maritime autonomous surface ships from a risk governance perspective: Interpretation and implications," *Safety science*, vol. 128, p. 104758, 2020.

[15] G. Li, L. Yang, S. Li, X. Luo, X. Qu, and P. Green, "Human-like decision making of artificial drivers in intelligent transportation systems: An end-to-end driving behavior prediction approach," *IEEE Intelligent Transportation Systems Magazine*, 2021.

[16] "Convention on the international regulations for preventing collisions at sea (colregs)," *International Maritime Organization*, 1972.

[17] "Remote-controlled and autonomous ships position paper," *DNVGL*, 2018.

[18] D. Ivanišević, A. Gundić, and D. Mohović, "Difficulties in understanding the colregs among the students from different systems of education for seafarers," *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, vol. 13, 2019.

[19] C. Livadas, J. Lygeros, and N. A. Lynch, "High-level modeling and analysis of the traffic alert and collision avoidance system (tcas)," *Proceedings of the IEEE*, vol. 88, no. 7, pp. 926–948, 2000.

[20] G. Zylius, "Investigation of route-independent aggressive and safe driving features obtained from accelerometer signals," *IEEE Intelligent Transportation Systems Magazine*, vol. 9, no. 2, pp. 103–113, 2017.

[21] G. Li, S. E. Li, B. Cheng, and P. Green, "Estimation of driving style in naturalistic highway traffic using maneuver transition probabilities," *Transportation Research Part C: Emerging Technologies*, vol. 74, pp. 113–125, 2017.

[22] Z. Chen, Y. Zhang, C. Wu, and B. Ran, "Understanding individualization driving states via latent dirichlet allocation model," *IEEE Intelligent Transportation Systems Magazine*, vol. 11, no. 2, pp. 41–53, 2019.

[23] G. Li, Y. Yang, T. Zhang, X. Qu, D. Cao, B. Cheng, and K. Li, "Risk assessment based collision avoidance decision-making for autonomous vehicles in multi-scenarios," *Transportation research part C: emerging technologies*, vol. 122, p. 102820, 2021.

[24] G. Li, Y. Chen, D. Cao, X. Qu, B. Cheng, and K. Li, "Extraction of descriptive driving patterns from driving data using unsupervised algorithms," *Mechanical Systems and Signal Processing*, vol. 156, p. 107589, 2021.

[25] Z. Li, L. Chen, C. Roberts, and N. Zhao, "Dynamic trajectory optimization design for railway driver advisory system," *IEEE Intelligent Transportation Systems Magazine*, vol. 10, no. 1, pp. 121–132, 2018.

[26] S. A. Shappell and D. A. Wiegmann, "The human factors analysis and classification system–hfacs," 2000.

[27] S.-T. Chen, A. Wall, P. Davies, Z. Yang, J. Wang, and Y.-H. Chou, "A human and organisational factors (hofs) analysis method for marine casualties using hfacs-maritime accidents (hfacs-ma)," *Safety science*, vol. 60, pp. 105–114, 2013.

[28] S. Yildiz, Ö. Uğurlu, J. Wang, and S. Loughney, "Application of the hfacs-pv approach for identification of human and organizational factors (hofs) influencing marine accidents," *Reliability Engineering & System Safety*, vol. 208, p. 107395, 2021.

[29] P. Sotiralis, N. P. Ventikos, R. Hamann, P. Golyshev, and A. Teixeira, "Incorporation of human factors into ship collision risk models focusing on human centred design aspects," *Reliability Engineering & System Safety*, vol. 156, pp. 210–227, 2016.

[30] T. Zhou, C. Wu, J. Zhang, and D. Zhang, "Incorporating cream and mcs into fault tree analysis of lng carrier spill accidents," *Safety science*, vol. 96, pp. 183–191, 2017.

[31] M. J. Akhtar and I. B. Utne, "Human fatigue's effect on the risk of maritime groundings–a bayesian network modeling approach," *Safety science*, vol. 62, pp. 427–440, 2014.

[32] J. Zhao and W. Price, "A statistical study of mariners'behaviour in collision avoidance at sea," 1996.

[33] T. Abramowicz-Gerigk and A. Hejmlich, "Human factor modelling in the risk assessment of port manoeuvers," *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, vol. 9, 2015.

[34] Z. Pietrzykowski, M. Wielgosz, and M. Breitsprecher, "Navigators' behavior analysis using data mining," *Journal of Marine Science and Engineering*, vol. 8, no. 1, p. 50, 2020.

[35] J.-B. Yim, D.-J. Park, and I.-H. Youn, "Development of navigator behavior models for the evaluation of collision avoidance behavior in the collision-prone navigation environment," *Applied Sciences*, vol. 9, no. 15, p. 3114, 2019.

[36] R. Zghyer and R. Ostnes, "Opportunities and challenges in using ship-bridge simulators in maritime research," *Proceedings of Ergoship 2019*, 2019.

[37] G. Li, R. Mao, H. P. Hildre, and H. Zhang, "Visual attention assessment for expert-in-the-loop training in a maritime operation simulator," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 1, pp. 522–531, 2019.

[38] D.-J. Park, J.-B. Yim, H.-S. Yang, and C.-k. Lee, "Navigators' errors in a ship collision via simulation experiment in south korea," *Symmetry*, vol. 12, no. 4, p. 529, 2020.

[39] B.-O. H. Eriksen, G. Bitar, M. Breivik, and A. M. Lekkas, "Hybrid collision avoidance for asvs compliant with colregs rules 8 and 13–17," *Frontiers in Robotics and AI*, vol. 7, p. 11, 2020.

[40] K. Woerner, M. R. Benjamin, M. Novitzky, and J. J. Leonard, "Quantifying protocol evaluation for autonomous collision avoidance," *Autonomous Robots*, vol. 43, no. 4, pp. 967–991, 2019.

[41] R. Zaccone and M. Martelli, "A collision avoidance algorithm for ship guidance applications," *Journal of Marine Engineering & Technology*, vol. 19, no. sup1, pp. 62–75, 2020.

[42] L. Kang, Z. Lu, Q. Meng, S. Gao, and F. Wang, "Maritime simulator based determination of minimum dcpa and tcpa in head-on ship-to-ship collision avoidance in confined waters," *Transportmetrica A: transport science*, vol. 15, no. 2, pp. 1124–1144, 2019.

[43] Z. Pietrzykowski and M. Wielgosz, "Effective ship domain–impact of ship size and speed," *Ocean Engineering*, vol. 219, p. 108423, 2021.

[44] H. Lyu and Y. Yin, "Colregs-constrained real-time path planning for autonomous ships using modified artificial potential fields," *The Journal of Navigation*, vol. 72, no. 3, pp. 588–608, 2019.

[45] Y. Huang and P. Van Gelder, "Time-varying risk measurement for ship collision prevention," *Risk Analysis*, vol. 40, no. 1, pp. 24–42, 2020.

[46] P. Wilson, C. Harris, and X. Hong, "A line of sight counteraction navigation algorithm for ship encounter collision avoidance," *The Journal of Navigation*, vol. 56, no. 1, p. 111, 2003.

[47] H. N. H. Oh, A. Tsourdos, and A. Savvaris, "Development of collision avoidance algorithms for the c-enduro usv," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 12 174–12 181, 2014.

[48] G. Li, H. P. Hildre, and H. Zhang, "Toward time-optimal trajectory planning for autonomous ship maneuvering in close-range encounters," *IEEE Journal of Oceanic Engineering*, vol. 45, no. 4, pp. 1219–1234, 2019.

[49] J.-H. Ahn, K.-P. Rhee, and Y.-J. You, "A study on the collision avoidance of a ship using neural networks and fuzzy logic," *Applied Ocean Research*, vol. 37, pp. 162–173, 2012.

[50] L. Zhao and M.-I. Roh, "Colregs-compliant multiship collision avoidance based on deep reinforcement learning," *Ocean Engineering*, vol. 191, p. 106436, 2019.

[51] Y. Hu, A. Zhang, W. Tian, J. Zhang, and Z. Hou, "Multi-ship collision avoidance decision-making based on collision risk index," *Journal of Marine Science and Engineering*, vol. 8, no. 9, p. 640, 2020.

[52] T. G. Monteiro, C. Skourup, and H. Zhang, "Using eeg for mental fatigue assessment: A comprehensive look into the current state of the art," *IEEE Transactions on Human-Machine Systems*, vol. 49, no. 6, pp. 599–610, 2019.

[53] G. Li, W. Yan, S. Li, X. Qu, W. Chu, and D. Cao, "A temporal-spatial deep learning approach for driver distraction detection based on eeg signals," *IEEE Transactions on Automation Science and Engineering*, 2021.

[54] R. Mao, G. Li, H. P. Hildre, and H. Zhang, "A survey of eye tracking in automobile and aviation studies: Implications for eye-tracking studies in marine operations," *IEEE Transactions on Human-Machine Systems*, vol. 51, no. 2, pp. 87–98, 2021.

Baiheng Wu (Student Member, IEEE) 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 (Senior Member, IEEE) 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.

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.

Hans-Ingar Johansen Aandahl received vocational education in the maritime education at Tromsø Maritime School (2011-2013), and in the nautical training at the Vocational School in Ålesund (2015-2017). He has been issued professional certificate of Competency Deck Officer Class 3 CoC. His vocational experience includes: apprentice sailor, cadet, first officer successively at Hurtigruten AS; first officer at Lovart AS; chief officer at Boreal Sjø AS. He is currently pursuing the bachelor degree in nautical science at Department of Ocean Operations and Civil Engineering, NTNU, Ålesund, Norway. He serves as the teaching assistant in a series of navigation courses.

Hans Petter Hildre is professor and head of the Department of Ocean Operations and Civil Engineering at the Norwegian University of Science and Technology (NTNU). His area of interest is product design and system architecture design. He is Centre Director for Centre for Research Driven Innovation (SFI-MOVE) within marine operations. This is cooperation between NTNU, SINTEF, University Sao Paulo and 15 companies at the west coast of Norway. Professor Hildre is head of research in national program Global Centre of Expertise Blue Maritime, project leader in several research projects, member of the board in 5 companies, and has a number of patents.

Houxiang Zhang (Senior Member, IEEE) 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.