Digital technologies can modify the decision-making process on ship bridges

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Abstract. Digital technologies have experienced fast growth over the last year with unexpected impacts on everyday life. The maritime sector is also positively affected by the introduction of new systems and technologies, especially in ship handling. The main reason behind adopting these technologies is to reduce human error, which could lead to serious accidents with massive repercussions on the safety of life at sea and the marine environment. Evaluating the impact on the bridge team's behaviour and the performance of the manoeuvre is a challenge and will help the future development of more advanced navigation systems.
This paper aims to test a decision support system that relies on a path-planning module suitable for collision avoidance using a bridge simulator. A test scenario has been set up to reproduce a familiar coastal navigation scenario where several ships navigate in a narrow area. The goal of the test is to avoid collisions by respecting the COLREG on a foggy day, ensuring the safety distance and the return on track. Experienced masters and inexperienced people have been involved in the testing procedure.
All the primary navigation information has been recorded and analysed both qualitatively and quantitatively, adopting dedicated metrics. The results prove that testing in a simulation environment can provide a valid test case and show that inexperienced personnel can also perform a safe escape route in compliance with international regulations.

Keywords. Autonomous Ship, Collision avoidance, MASS, Decision support system.

1. Introduction

The integration of Information and Communication Technologies (ICT) into maritime operations has significantly transformed the current ship operations. Systems such as Electronic Chart Display and Information Systems (ECDIS), Automatic Identification Systems (AIS), and Automatic Radar Plotting Aid (ARPA) have become the standards for safe navigation. Crew members must be trained to ensure the effective use of these technologies. Marine simulators have been used for several years, offering

realistic and controlled environments for seafarers to develop and keep updated their skills in operating onboard systems [1].
Marine simulators have evolved from basic navigational aids to complex platforms capable of replicating every type of maritime scenario. Their fidelity has been enhanced through advancements in computational power and modelling techniques, enabling the accurate simulation of vessel dynamics and including environmental conditions [2].

Extensive research underscores the efficacy of marine simulators in training bridge crews on new ICT technologies. In [3], a questionnaire-based assessment of training in a marine simulator is proposed, highlighting the positive impact on trainees' competence and confidence in utilising advanced systems. Furthermore, as reported in [4], the integration of game-based learning approaches showcases innovative methodologies to enhance maritime education and training.

While the effectiveness of marine simulators in training bridge crews in navigation is well established, their use for testing and evaluating new domain-specific ICT technologies remains a less explored area.

Simulators offer a risk-free environment where testers can familiarise themselves with new systems, practising decision-making without the consequences of real-world errors. Moreover, intensive virtual testing can lead to the discovery of hidden bugs or malfunctioning of the system under test without the availability of a real ship.

The motivation behind this study starts from the critical role that human factors play in maritime accidents [5], and the primary goal of this paper is to investigate the effectiveness of using maritime simulators in testing an innovative navigation tool for decision-making support in case of potential collision risks, COLREG-compliant [6], namely Decision Support System (DSS).

Despite technological advancements, the competence and preparedness of the crew remain crucial in ensuring safe navigation. By leveraging marine simulators for ICT training, it is possible to bridge the gap between technological implementation and human operation, leading to a smooth transition for MASS level 1 ships.

Testing has been performed in the SHip in the Loop (SHIL) research infrastructure, fully described in [7], available at the University of Genoa.

Unlike standard commercial simulators designed primarily for training, SHIL provides a flexible research environment that systematically integrates and evaluates external hardware and software modules. Among its benefits, this flexibility enables experimentation and validation of next-generation autonomous ship technologies and remote operation centres [8], and supports the development of innovative solutions beyond the constraints of conventional simulators.

The paper structure is reported hereinafter. The hardware and software used for the testing are described in Section 2. Section 3 reports the testing procedure, including the scenario description, the goal and constraints, and the metrics used for evaluating the outcomes. The results and the discussion are reported in Section 4. Eventually, in Section 5, the conclusions are drawn.

2. Research Infrastructure and Materials

The proposed testing procedure was done in the University of Genova laboratory using the SHip in the Loop (SHIL) infrastructure. The main control station is a maritime simulator composed of software modules and related hardware to simulate a ship's dynamic behaviour and its systems in a virtual scenario.

The overall system enables control of the virtual ship operating in a realistic synthetic scenario. It consists of a scalable set of standard dashboards and hardware equipment for the controls of ship management, navigation, and communication functions.

2.1. Class B bridge simulator

The simulator enables the simulation of vessels, with their physical hydrodynamic behaviours accurately reproduced, allowing a ship to be steered with interfaces that can be traced back to real vehicles and are therefore intuitive for experienced pilots; it thus allows accurate manoeuvres to be performed in a marine scenario while enabling simulations of port manoeuvres.

Software-wise, the system is subdivided into functional modules capable of operating independently. All modules communicate with the system via Ethernet using specific and standard communication protocols [9].

Figure 1 depicts the Class B bridge simulator used for the investigation.

Figure 1**.** Bridge Simulator Overview.

The main features of the testbed are:

- object-oriented architecture, referring to the widespread software development standards, which allows easy maintenance and proper and simple evolution;
- guarantees improvements and new features with direct interventions or with specific new plugin developments;
- quality according to the UNI-EN ISO 9001: 2000 standard and RINA STCW certification;
- interoperability with external software and hardware components;
- supports remote accessibility to enable users to conduct activities without physical presence and facilitates collaboration with external specialists.

In **Table 1**, the main modules of the simulator are listed and described.

2.2. Decision Support System

The DSS and its Graphical User Interface (GUI) are installed on a separate workstation, and its development is based on previous research [10], [11]. The DSS and the GUI communicate with the simulator using NMEA according to the standard onboard configuration; the overall architecture of the integration pipeline is reported in Figure 2.

Table 1. Simulator modules description.

Module	Description
Radar Antenna	Navigation radar signal generator. Data generated from the 3D virtual environment simulating a real radar antenna.
Radar GUI	Software module reproducing a Plan Position Indicator that supports the main functionalities of a standard radar system, including ARPA capabilities.
ECDIS	Commercial plotter receiving data from virtual sensors according to the NMEA standard.
Instrument	VConning virtual tools, indicators and customisable controls.
VIS	Multi-camera, multi-channel, stereoscopic 3D, HUD Render of the operating scene in several weather and sea conditions.
Instructor Manager	Instructor module for synthetic scenario management: mission creation and real-time management of all parameters related to entities and the simulation environment, such as: entity location, environment definition, vehicle definition, sensors and effectors, fault management, simulation time, and weather conditions.
Manoeuvrability	Physics engine that applies the non-linear mathematical model of the ship's hydrodynamic and propulsion behaviour to generate its motion.
Remote Access	Provides a secure connection for remote access to the simulator. It enables the interaction with the main functionalities of other modules and the capability of overseeing simulation sessions.
COMMAN	Software engine that manages data interchange traffic between System modules.

In detail, the data from the virtual sensor and the five video streams composing the operating scene are sent to two local servers. These data are used as input for the data fusion layer [12], which provides the necessary information on the targets for the DSS. The information serves as the input for the detection module, which continuously monitors for potential collision risks. If a risk is identified, the module activates the COLREG Classification Module [13] to determine the relevant COLREG scenario and applicable rules. Using this information, the Route Selection Module can recommend a course adjustment to prevent a collision [14].

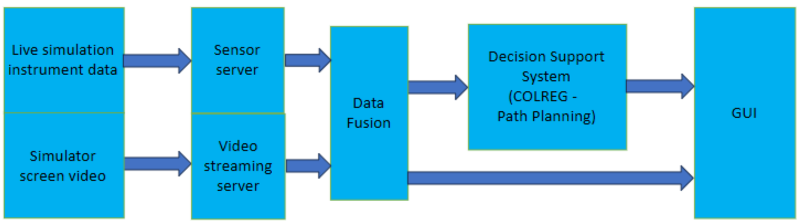

Figure 2. Integration pipeline.

Once the COLREG scenario is identified and the evasive manoeuvre is planned, the GUI displays the system's outcomes, as shown in Figure 3. The evasive manoeuvre is provided by a set of waypoints and pictured on the maps. On the 3-D visualisation, the suggested new course, the COLREG needs to be satisfied, and the data on the obstacles are reported. The tester can choose to follow the DSS recommendations or make an independent decision, using the Human-Machine Interface (HMI) to control the rudder helm or set the autopilot.

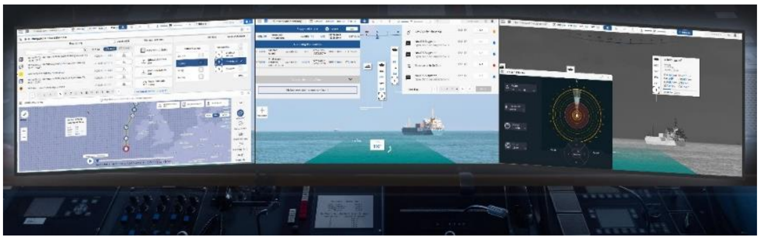

Figure 3. Overview of the GUI outcomes.

3. Testing Procedure

3.1. Scenario Description

The initial conditions of the proposed scenario, for reproducibility purposes, are reported in **Table 2**.

Table 2. Initial conditions.

SHIP TYPE	SOG_1 [kn]	HDG_1 [°]	λ_1[°]	φ_1[°]
Naval Vessel (own)	18.0	270.0	44.371155	8.967225
Bulk Carrier	12.0	200.0	44.391155	8.920753
Sailing Boat	6.0	340.0	44.354489	8.897518

The own ship, represented by the blue waterline, navigates with a constant speed of 18 kn pointing 270°. On the starboard side, a bulk carrier navigates at 12 kn heading to 200°, creating a crossing situation between power-driven vessels (Rule 15). In the meantime, in the scenario, it is also present, on portside, a sailing boat showing a cone with the apex down. Even in this case, it is necessary to apply Rule 15.

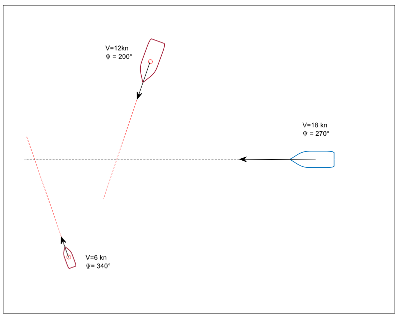

Figure 4. Testing scenario setup.

3.2. Goal and constraints

The scope of the test is to perform a COLREG-compliant evasive manoeuvre, respecting a CPA of 0.5 nautical miles, and eventually to return to the original track.

Four testers have been involved in the trials: two experienced masters and two persons with no maritime background. The two masters used only their knowledge and experience to handle the own ship while the two novices could rely, with a separate screen, on the real-time suggestions from the DSS. Each test lasts 15 minutes, and all the data have been recorded and analysed as reported in the following.

3.3. Results analysis

Defining Key Performance Indicators (KPIs) for a ship manoeuvre is crucial to ensure objective evaluation, enhance safety, improve efficiency, and facilitate continuous improvement in operational performance. In this specific case, five different KPIs have been applied to have a quantitative approach to compare the evasive manoeuvre.

The first one is the path smoothness $\sigma(R)$, which could represent the energy used to perform the manoeuvre evaluated based on the course changes. It is calculated as follows:

$$\sigma(R) = \frac{1}{N-2}\left(\sum_{i=1}^{N-1} \theta^2(s_i, s_{i+1})\right)^{\frac{1}{2}} \quad (1)$$

where: R is the route identified by a set of N waypoints, θ is the course change between two consecutive legs s. s is identified as the couple of starting and ending coordinates of each waypoint.

The second metric presented is the path elongation $L(R)$. It represents the additional track needed to perform the manoeuvre. This index is strongly related to fuel consumption and expected arrival time (ETA), assuming the ship's speed changes are negligible. It is defined as:

$$L(R) = \frac{\sum_{i=1}^{N} |s_i|}{|\boldsymbol{x}_{end} - \boldsymbol{x}_{start}|} \quad (2)$$

where: $\boldsymbol{x}_{end}$ and $\boldsymbol{x}_{start}$ represent the starting and ending coordinates of the manoeuvre, while $|s_i|$ is the leg's length.

The Minimum Closest Point of Approach (CPA) is a well-known metric for such kind of evaluation and indicates the shorter distance from the target encountered during the evasive manoeuvre. It is related to the safety aspect:

$$CPA_{min}(R) = min_{i\in\{1,\ldots,N\}}\left(min_{m\in\{1,\ldots,M\}} CPA_m(s_i)\right) \quad (3)$$

The maximum track error $T(R)$ provides the deviation from the original route. It is calculated in non-dimensional form:

$$T_{max}(R) = max_{i\in\{1,\ldots,N\}} \frac{s_i \cdot \boldsymbol{u}}{|\boldsymbol{u}|} \quad (4)$$

The speed reduction, ΔSOG, is the last proposed KPI. It indicates the maximum drop of speed as a percentage of the initial one:

$$\Delta SOG = \frac{SOG_1 - min_{i\in\{2,\ldots,N-1\}}(SOG_i)}{SOG_1} \tag{5}$$

where: SOG_1 is the speed over ground at the starting time.

4. Results

Figure 5 to Figure 8 report the evasive manoeuvres that were conducted. In all the figures, the continuous black line represents the route provided by the collision avoidance algorithm, while the black circles represent the corresponding waypoints. The blue waterlines represent the trajectory of the own ship, while the red ones represent the trajectories of the two targets.

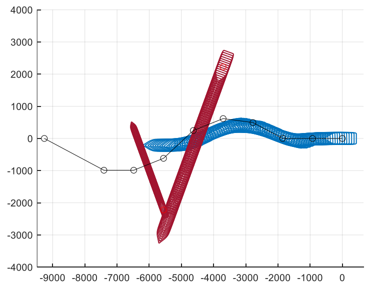

Figure 5. Manoeuvre performed by *Master*$_1$ without using DSS.

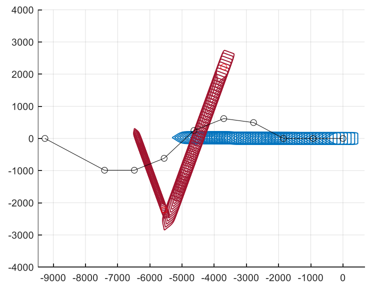

Figure 7. Manoeuvre performed by *Master*$_2$ without using DSS.

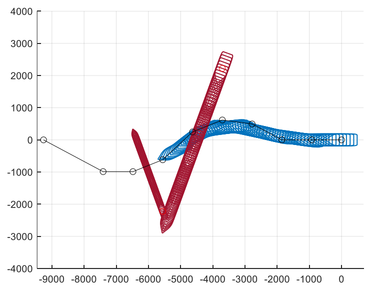

Figure 6. Manoeuvre performed by *Novice*$_1$ using DSS.

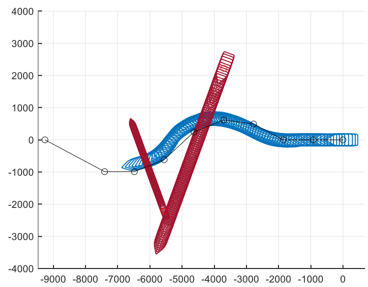

Figure 8. Manoeuvre performed by *Novice*$_2$ using DSS.

Looking at the trajectories performed by the two masters, the different approaches used stand out. Master$_1$ preferred to keep the speed constant while performing light turns, while Master$_2$ preferred to reduce the speed without acting on the rudder. It is worth noticing that both manoeuvres are COLREG-complaint, and this highlights once again how COLREG can be interpreted and can lead to misunderstanding, making the

implementation in software as "strict rules" challenging. The two novices unquestioningly tried their best to reproduce the manoeuvre suggested by the DSS.
Figure 9 reports the aggregated results applying the five metrics to the four manoeuvres. $Master_2$ performed the smoothest manoeuvre, no elongation with respect to the original track was experienced, but the speed reduction led to a longer time to manoeuvre with a potential increase in fuel consumption to reaccelerate. The other three testers performed similarly, with the two novices using the DSS filling the gap (in terms of experience) with $Master_1$.

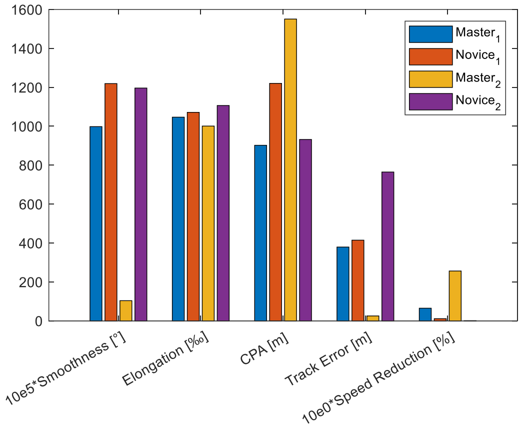

Figure 9. Metrics comparison.

5. Conclusions

The study proposed a procedure involving humans in the loop to test a decision support system for avoiding collisions with four participants with different sea experiences. Moreover, a benchmark and specific KPI for comparing the results are suggested. The results obtained for the testing show how digital technologies applied to the maritime sector can allow inexperienced people to perform a complex manoeuvre that requires years of training and navigation at sea.
The number of tests carried out is limited; indeed, no relevant statistics can be obtained. This last point could be the object of future study, increasing the number of testers and diversifying their experience; a potential improvement is showcasing additional COLREG scenarios.
The bridge simulator infrastructure enabled testing of the DSS as if it were connected to a real onboard network, using the same data exchange protocols. Moreover, it allowed for creating meaningful test cases with potentially hazardous scenarios and engaging individuals with different levels of navigation expertise and technological familiarity.
This experience proves that bridge simulators are promising assets for testing new ICT solutions for the maritime domain in a safe and realistic condition.

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