MTEC-ICMASS-2022 IOP Publishing
Journal of Physics: Conference Series **2311** (2022) 012025 doi:10.1088/1742-6596/2311/1/012025

Development of Recommendations for Digital Testing of MASS Navigation Safety prior to Sea Trials

Kie Hian CHUA[1], Savio COUTINHO[2], Aizad NORAHIM[1], Dimitrios KONOVESSIS[3]

[1]Technology Centre for Offshore and Marine, Singapore (TCOMS), 12 Prince George's Park S(118411),
[2]Singapore Polytechnic, 500 Dover Road S(139651),
[3]University of Strathclyde, 16 Richmond St, Glasgow G1 1XQ, United Kingdom

Corresponding author: chua_kie_hian@tcoms.sg

Abstract. For Maritime Autonomous Surface Ships (MASS), a key area that has seen active development is in the use of autonomous capabilities for vessel navigation and control. This can range from a simple use case of waypoint navigation, which takes into account bathymetry and navigation markers, to complex collision avoidance scenarios where the autonomous systems are required to detect, evaluate and execute evasive manoeuvres based on time and spatially varying dynamic behaviour of other vessels. In Singapore, it has been identified that there is a need to carry out accurate digital testing of MASS navigation safety before sea trials. This is where a vessel developer is required to demonstrate that the MASS is able to carry out the sea trials safely, and to stress test high risk scenarios that may not be practicably tested in the sea trials. A study has been carried out to develop recommendations for the digital testing, which takes into consideration the need for accurate representation of the actual MASS being built, as well as the verification of the autonomous navigation algorithm's capabilities to safely control the vessel in real-world scenarios. Based on the study, a three-stage framework is proposed. Firstly, the accuracy of the digital model in representing the dynamic responses of the actual vessel is verified and any discrepancy with benchmark data is to be quantified. Secondly, tests are carried out to ascertain that the autonomous navigation algorithm is able to control (virtually) the dynamically-accurate vessel from one point to another, taking into account the real-world environmental loads. Lastly, the ability of the autonomous navigation algorithm in carrying out collision detection and avoidance is verified. As part of the study, a review of the current state-of-art and engagement with the industry has been carried out. These details are described in this paper.

1. Introduction

With the advancement of digitalization in the maritime industry, autonomous or remotely controlled operations could undertake mundane and high-risk tasks, thereby enhancing efficiency and safety and efficiency. This has helped increase the interest in autonomous or remotely controlled vessels.

Globally, several companies are actively developing and integrating technologies to automate and autonomise maritime navigation and operations. Since 2017, Kongsberg Maritime has been involved in the development of navigational, power generation and propulsion systems for the Yara Birkeland which has been launched in Jan 2022 [1]. Wärtsilä is also actively developing autonomous solutions, starting from ferries and harbour tugs. In 2020, Wärtsilä and PSA Marine [2] retrofitted an existing tug with a suite of sensing and control systems, and have successfully demonstrated the autonomous capabilities through a series of sea trials, under the IntelliTug project. MPA has also funded other MASS projects, including the retrofitting of 2 other tugs with autonomous capabilities by ST Marine [3] and Keppel Offshore and Marine [4], respectively.

Despite the examples above, the maritime autonomy sector is generally still considered to be in its early stages of development. At the current state-of-the-art, autonomous navigation requires the integration of navigational, propulsion and control systems that require continuous improvements due to the evolving global maritime traffic and unpredictable sea conditions.

As part of the effort to enable MASS trials and operations, a study has been carried out to develop a set of recommendations for digital testing of autonomous navigation capabilities prior to actual sea trials. These recommendations take into consideration the need for accurate representation of the actual MASS vessel being built, as well as the verification of the autonomous navigation algorithm's capabilities to safety control the vessel in real-world scenarios. In addition, any recommendations put forward for MASS testing should not impede technology innovation, and should consider the goal-based processes used by the industry for qualifying MASS.

In our study, literature from current research and technical practice is reviewed, as well as with actual data from initial MASS sea trials that have been carried out in a "sandboxed" manner in Singapore waters. Based on the review and engagement with stakeholders, an underlying framework is first developed, addressing the need for first-principles, verification of vessel model accuracy, as well as the autonomous navigation algorithm's ability to steer the vessel safely (in the virtual representation), including navigation under the dynamic influence of environmental loads, as well as the algorithm's collision avoidance capabilities.

To establish equivalence in terms of navigation safety, the digital testing will gauge whether an autonomous navigation algorithm can achieve safe distances that are comparable to existing manned vessels. Quantitative and qualitative data on the typical closest point of approach (CPA) for various vessel manoeuvring scenarios is collected to establish the existing benchmark for the manned vessels. AIS data of ships plying around Singapore is used to quantitatively establish the CPA between a vessel and another encountered vessel or navigational marker. At the same time, qualitative data is also gathered from mariners, based on their perception of CPA as they navigate through the same scenarios in Singapore waters.

In the next section, an overview of the research and technical literature is reviewed. This is to provide the background of the existing state of the art and the current industry practice relating to testing and verification of autonomous vessel safety. In Section 3, the frameworks established by the various Classification Societies for qualification and certification of autonomous vessels and the associated technological capabilities are also reviewed. Section 4 describes how CPA values that can be used to demonstrate safety equivalence to the existing conventional vessels are determined from AIS data and through a survey of seafarers. Lastly in Section 5, we present the proposed digital testing framework before concluding in Section 6.

2. Literature Review

There have been various developments using smart or autonomous algorithms to provide navigation guidance, including obstacle detection, trajectory control, and collision avoidance. A selection of the relevant literature has been reviewed and are disused below.

2.1. *Autonomous navigation and collision risk assessment*

In [5], the authors proposed a fuzzy control way point tracking system that calculates the proximity of the first two waypoints individually using distance to closest point of approach (DCPA) and time to closest point of approach (TCPA) and then subsequently plan out the appropriate route. The authors also noted that the differing manoeuvring characteristics of different vessels could pose a challenge for way point tracking systems.

Given the dynamic nature of ship navigation, information relating to positioning, navigation, and timing (PNT) is crucial in ensuring navigation safety due to the need to determine the relative positions between ships and / or obstacles, including the evolution of the trajectories. The use of AIS as a tool to provide PNT information is investigated in [6] by using the signals from different AIS stations. A ship's position can be predicted based on the associated displacement vector.

While the AIS can give real-time information between nearby ships and the operation of encountered ships, it is not able to provide a broad interpretation for a vessel to take any evasive actions to reduce a collision risk. In [7], the authors proposed a new design of AIS-based embedded system for vessel collision avoidance that provides visual display information of the vessel navigation for the mariners and provide advance collision warning and operation plan. A framework for collision warning using a risk model where the ship's system states, and position-related information are used in [8] to determine the level of risk of a ship-to-ship collision.

To ensure the safety of the autonomous ship, online assessment of navigational information should be carried out in real-time, similar to how existing ships maintain constant watchkeeping. The following two categories of collision risk detection method are proposed in [9]: Closest Point Approach Method (CPA - 2D method) and Predicted Area of Danger Method (PAD - 3D method). In the former, the predicted shortest distance between an autonomous ship and an encountered vessel is used to assess the collision risk. In the PAD method, various possible trajectories of the autonomous ships is projected as an inverted cone, while the encountered ship's trajectory is projected as an inverted cylinder. The intersection between the cone and cylinder is considered to be the area of danger where there is a risk of collision.

2.2. Assessment and Regulation of Autonomous and Remotely Operated Vessels.

In [10], the potential impact of autonomous and remotely operated vessels on the overall regulatory framework is discussed and a goal-based regulatory approach is proposed to facilitate the use of various technologies. An approach to apply the Systems-Theoretic Process Analysis (STPA) for the holistic safety verification for autonomous ships is proposed in [11], where a case study for an autonomous ship, covering hazard identification for potential scenarios involving collisions into obstacles and loss of navigational control at a high-level is also described. A system developed by DNV GL for testing of autonomous navigation systems using a ship's Digital Twin is described in [12]. Other main components of the system include the Operating environment, Test management system, and the Test interface that could be used for evaluating how well the autonomous navigation system performs based on compliance with COLREGs.

With regard to the generation of scenarios for digital testing, there are also other developments in terms of how scenarios could be generated for testing of collision avoidance capabilities. In [13], the authors developed a data-driven approach based on AIS information to generate traffic scenarios for collision avoidance testing. Machine learning techniques for feature extraction is applied for abstraction and automatic identification of various ship encounter scenarios such as passing, crossing of other vessels. A method for automatic generation of hazardous scenarios for the testing of an autonomous ship's collision avoidance system based on the distance and time considerations between the ship and the encountered vessels is proposed in [14].

2.3. Quantifying the collision regulations into actionable algorithms

Since its origins in 1840, the COLREGS have been written in a general manner, requiring interpretation by seafarers taking into account the circumstances, which includes a combination of the specific COLREG rule and on what is commonly referred to as "the ordinary practice of seamen". This term, mentioned in Rule 2, relates to the prevalent culture of the area being navigated. While this rule requires compliance to COLREGS it also allows for deviation when it is necessary to avoid immediate danger. COLREGS does not provide information on the deviations nor definition of what could constitute "ordinary practice of seamen." Thus, the challenge for navigation decision making is to identify the appropriate time horizon and spatial distance before determining it is required to deviate for collision avoidance. This decision is dependent on an assessment of the prevailing circumstances where the following considerations should be taken into account by the navigator:

i. Size, speed and manoeuvrability of the vessels involved.
ii. Available safe sea room.
iii. Location and number of other vessels in the vicinity which could increase the complexity of the situation.
iv. Influence of environmental aspects, such as, visibility, state of sea, current etc.

There are other COLREG rules that have been laid out in a general manner similar to Rule 2. For example, in Rule 16 a give-way vessel is required to "take early and substantial action to keep well clear." The subjectivity of this rule poses a challenge as to what would constitutes "early and substantial" action, which in turn could be any combinations of speed or course change. Rule 17 requires the stand-on vessel to monitor if the other vessel is taking action in accordance with the appropriate rules and monitor of this action is made in ample time and allows for safe passing of both vessels. Such a vessel is required by another part of the same rule to take action when collision cannot be avoided by the action of the give-way vessel alone. With the subjective terms such as "action as will best aid to avoid collision" and "if the circumstances at the case admit", Rule 17 adds further complexity to implementation of autonomous collision avoidance strategies.

In a high complexity situation however such as the Straits of Malacca and Singapore where there is heavy vessel traffic in a constrained sea space, an evasive manoeuvre for one ship may lead into a close quarters situation with another ship, resulting in a cascade of complex and unpredictable interactions and outcomes. In [15], it is suggested that a study of Automatic Identification System (AIS) data for a given area could be undertaken to elucidate the effective outcomes of "early and substantial" actions undertaken in a manner that is consistent with "the ordinary practice of seamen" for the area. By combining learning from recent AIS data with large number of digital simulations, developers would be able to ensure that the limits identified are up-to-date with respect with respect to the "ordinary practice of seamen" in the area, which will evolve as the overall vessel demography changes with increase in adoption of autonomous technologies. This would also pave the way for development of "learn-as-you-operate" capabilities where the navigation knowledge and experience derived from machine learning or artificial intelligence (AI) is improved with more data that is kept updated.

3. Development in Qualification and Certification of MASS

Various Classification Societies, in their role as Recognized Organizations for flag Administrations, have published guidance on the certification of MASS. A selection of these guidance documents is reviewed in our study, in order to elucidate the current approaches on how MASS and the system components can be qualified as fit-for-purpose.

3.1. American Bureau of Shipping (ABS)

ABS defined a five-stage goal-based qualification process [16], which requires comprehensive engineering evaluation and detailed risk assessments to be done at each stage. The five stages of the process are: Feasibility, Concept Verification, Prototype Validation, System Integration, and Operational. The two sets of guidance notes from ABS [16] and [17] can be used for the purpose of classifying ships and offshore vessels integrating new technologies which have yet to be proven and tested in the maritime and offshore industry, such as the novel systems that are used in MASS. In addition, an accompanying procedure [18] provides further guidance on the smart capabilities that can be implemented on existing vessels, that can be used to enhance the safety and efficiency.

3.2. Bureau Veritas (BV)

BV has developed a risk-based guideline to classify new technologies in the marine and offshore industry. The objective of this risk-based systematic approach is to locate the risks associated with the failure modes identified from this new technology [19]. BV has also published a set of Guidelines for autonomous shipping [20] which provides recommendations for the operation and design of the autonomous systems, to help the designers and operators of these autonomous systems better understand the regulatory framework governing this type of ships.

3.3. Det Norske Veritas (DNV)

DNV has published a set of recommended practice (RP) which provides guidance for the qualification of new concepts and technologies [21]. The RP provides a staged qualification process for identifying and minimizing unpredictability of these technologies, through technical evidence demonstrating the performance of associated systems. The process compromises six stages: Qualification Basis, Technology Assessment, Threat Assessment, Qualification Plan, Qualification Execution and Performance Assessment. DNV has also published the Class Guideline (CG) for Autonomous and Remotely Operated Ships [22], providing recommendation for operation, design, as well as the qualification process for certification of MASS. The CG states the rationale for adopting a risk-based assurance process, i.e. that the MASS sector is still in the nascent stages where novel technologies and concepts are being introduced and it "is therefore currently not possible or desirable to provide detailed rules for all areas and combinations of concepts".

3.4. Lloyd's Register (LR)

Consistent with other Classification Societies, LR introduced a structured goal-based approach to the qualification process of unmanned marine systems (UMS) with a defined set of goal, functional objectives, and performance requirements [23 & 24]. LR's rationale for adopting a goal-based approach is similar to DNV's rationale for adopting a risk-based assurance process.

4. Determination of CPA from AIS Data and Survey of Seafarers

Given the above, an exercise to analyse AIS data on actual closest point of approach (CPA) for various types of ships in the Singapore Strait is undertaken. As described earlier, such CPA can be inferred to be 'safe outcomes' that a typical vessel should adhere to ensure safe navigation, given the "ordinary practice of seamanship" in this area. This AIS data was captured using an AIS receiver located at the National University of Singapore (NUS), which provided information on vessel movement in the western part of the Singapore Strait. This is shown in the red circle of Figure 1.

Figure 1. AIS data coverage of NUS receiver

Data over a period of 5 months from April 2020 to August 2020 was collected for the following types of vessels and for the manoeuvres as indicated in Table 1. From the AIS data, it was observed that while the CPA values may vary according to the type of vessel, the range of variation is less than half a nautical mile for each type of manoeuvre. This is likely due to the influence of a restricted waterway dominating over the vessel type. Consequently, a condensed table of the CPA values was obtained and shown in Table 2.

Table 1: Types of vessels and manoeuvres studied using the NUS AIS data

Types of vessels for which AIS data recorded	Manoeuvres for which AIS data recorded
• Bulk Carrier • Oil Tanker • Offshore Vessel • Container Vessel • Passenger Vessel/Ferry • Ro-Ro Vessel	• Passing ahead of another vessel • Passing astern of another vessel • Passing alongside another vessel (head-on or overtaking situation) • Passing a fixed navigation mark

Table 2. Ranges of CPA values according to types of manoeuvres

Manoeuvre Type	CPA range derived from AIS data
Passing ahead of another vessel	0.56 – 0.63 NM
Passing astern of another vessel	0.55 – 0.61 NM
Passing alongside another vessel (head-on situation)	0.61 – 0.72 NM
Passing a fixed navigation mark	1.10 – 1.50 NM

A survey of past and present seafarers with experience navigating the Singapore Strait is also conducted to further ascertain the value of similar safe distances for the manoeuvres is listed in Table 1. The following questions were posed to the participants through the survey:

i. In a risk of collision situation during transit in the Singapore straits, what CPA would you deem to be safe and appropriate when passing ahead of the other vessel?
ii. In a risk of collision situation during transit in the Singapore straits, what CPA would you deem to be safe and appropriate when passing astern of the other vessel?
iii. In a risk of collision situation during transit in the Singapore straits, what CPA would you deem to be safe and appropriate when passing clear of the other vessel in an overtaking or head-on situation?
iv. In a situation during transit in the Singapore straits, what CPA would you deem to be safe and appropriate when passing clear of a fixed navigation mark?

A total of 179 respondents were recorded through the survey, a breakdown of their respective rank at time of completion of survey is shown in Table 3 while Table 4 tabulates the results on the expected CPA obtained from the survey, together with the ranges derived from AIS data.

Table 3. Breakdown of seafarer survey participants by rank

Seafarer Rank	No. of respondents
Master Mariner	72
Chief Officer/First Mate	28
Navigational Officer (Operational)	50
Trainer/Lecturer	15
Sea-Pilot	9
Shore-Based (ex-seafarer)	5

Table 4. CPA ranges obtained from seafarer survey compared with ranges derived from AIS data

Survey Question	CPA Ranges (NM)	
	Seafarer	AIS
1	0.97 – 1.14	0.56 – 0.63
2	0.62 – 0.73	0.55 – 0.61
3	0.68 – 0.75	0.61 – 0.72
4	0.41 – 0.51	1.10 – 1.50

The following observations were made from the CPA ranges obtained from the survey:

i. The CPA values obtained from the survey is expected to be more conservative due to the perception of a navigator exercising prudence, to maintain a higher level of safety, especially for Question 1.

ii. There is general consistency between the two datasets for Questions 2 and 3.

iii. For Question 4, the difference in CPA values is likely due to the way AIS calculates CPA which uses the actual centre of the navigation mark as a reference point. Seafarers on the other hand, would usually consider the edge of landmass on which the navigation mark is situated as the point of reference for determining CPA.

iv. While good seamanship dictates variable safe distances be maintained from passing vessels or objects based on ship length, ship speed and size to take into account special manoeuvring characteristics of vessels, the CPA ranges obtained above from both the AIS data and seafarer survey are in the order of around 0.60 to 0.75NM for most cases. This is attributed to the unique context Singapore Strait where the high volume of traffic navigating in close quarters due the limited sea room at hand play a more dominant influence on the CPA compared to the vessel sizes.

Based on the above study and taking into consideration that the recommendations on digital testing of autonomous ships should be kept as simple as reasonably practicable to facilitate harmonised implementation across different stakeholders, it is recommended that a CPA range of 0.60NM – 0.75NM should be adopted for the various indicated manoeuvres and interactions with other target vessels / obstacles. This would suffice to demonstrate that the autonomous ships are able to achieve safety outcomes that are equivalent to the existing ships navigating in this area. Through the industry and seafarer engagements, there was also a request for simplicity in terms of specifying any recommendations of CPA for MASS. As such, the range of 0.60NM – 0.75NM is also applied to the scenario when a MASS passes a fixed navigation mark. In addition to having a simple and standardised metric for assessing the collision avoidance capabilities of an autonomous ship, this CPA range also provides an additional safety buffer distance compared to the range of CPA values obtained from the seafarer survey, as well as the AIS data (after accounting for the manner in which CPA is computed by AIS systems).

5. Recommended Digital Testing Framework

A three-stage digital testing framework is proposed based on the foregoing review. Descriptions of each of these stages are described below.

The first stage, Model Accuracy, is to first ensure that the underlying numerical model of the ship within the digital model is verified to be reliable and accurate before conducting the simulation test cases using the autonomous navigation algorithm. This is carried out by using the numerical model to simulate turning circle and zig-zag manoeuvres, and comparing against benchmark data of the actual ship. These manoeuvres have been selected from the IMO Standards for Manoeuvrability [25] and are thus familiar to the industry.

In the second stage, Navigation Safety, the digital model will be tested for its ability to autonomously navigate from one point to another, such as along a series of waypoints in various environmental conditions. This is to demonstrate that the autonomous navigation algorithm is able to steer the ship safely, accounting for the external environmental forces the bathymetry and coastline.

In the third stage, Collision Detection and Avoidance, the collision avoidance capabilities of the autonomous ship will be assessed, where the autonomous ship is required to take action in accordance with COLREGS, allowing for safe passing maintaining a pre-determined safe distance. By defining incidents as breaches of a prescribed safe distance and setting the incident tolerance level to be the same as the current level, the framework helps to ensure that the autonomous vessel is at least as safe as the existing ships in operations.

The parameters used for the second and third stages would depend on the relevant context, such as the operating area of the autonomous ship, and considers the need for a goal-based approach as recommended by the industry and IMO. Through our industry discussions, representatives stressed the criteria for such tests to adopt a functional approach, where the autonomous ship is tested for functions and goals it is designed and built to perform. Nevertheless, the advantages for standardization of the tests to ensure a harmonised degree of rigour, to provide a level playing field across industry stakeholders is also recognised, and to minimize the likelihood of differing interpretations by different stakeholders. As such, in the second Navigation Safety stage of the digital testing, a set of prescribed environmental conditions based on conditions normally encountered in this region is proposed. For autonomous ships operating in other areas in addition to Singapore, environmental conditions applicable to that area should be applied in addition, to ensure that the navigation algorithm is able to account for those environmental effects. Considering that there would be a certain level of uncertainty and the need to demonstrate that the navigation algorithm is able to generate consistent results across multiple simulation runs, the point A to point B navigation tests should be repeated 30 times, to quantify the prediction interval of the navigation course travelled by the digital model.

Based on a similar consideration for standardisation, collision avoidance testing of typical COLREGS scenarios in the third Navigation Safety stage should be progressively tested up to a minimum of two encountered target vessels. For these test scenarios the autonomous ship will be required to take avoiding action in a risk of collision situation involving one or two target vessels. The action taken shall be in accordance with COLREGS and allow for safe passing based on a pre-determined safe distance. Based on the simulated outputs, this safe distance will be obtained in the form of the CPA between the autonomous ship and encountered vessels. Corrections to account for discrepancies between the digital model and the actual vessel, as well as uncertainty of the prediction should be applied to the CPA. Thereafter, the corrected CPA will be assessed against the CPA values recommended in the previous section, as a “pass criteria”. In addition to the CPA, the actions taken by the autonomous ship should be in accordance with COLREGS. Thus, the digital model should be deemed to have failed a test case if it undertakes an action that is not aligned with COLREGS or where the obtained CPA is less than the recommended values.

The following combinations of ship speed and draught conditions are recommended for the digital tests.

Ship speed

a. 6 knots;
b. 12 knots; and
c. At least 90% of the ship’s speed corresponding to 85% of the maximum engine output, as per the IMO Standards for Manoeuvrability [25]

Draught condition

a. Full load or design draught; and
b. Lightly loaded or ballast draught.

The ship speeds have been selected based on the speed limits within the Singapore Port waters, as well as the speed specified in [25]. By testing at both higher and lower speeds, any influence of ship speed on manoeuvrability would be taken into account. Similarly, by testing at the heaviest and lightest loading conditions, the influence of vessel loading (including weight distribution) on the dynamic responses would be taken into account.

5.1. Stage 1: Model Accuracy

In a digital model for motions of a dynamic system, the motion responses of that system under external forces would be captured using a set of mathematical equations. For an autonomous ship, these equations would be implemented as a manoeuvring model, upon which the autonomous navigation and collision avoidance capabilities will be built on. It is thus important to establish the accuracy of the manoeuvring model as inaccuracies could mean erroneous predictions of an autonomous ship’s ability to manoeuvre away from shallow waters, obstacles and other vessels, resulting in grounding or collisions. As such, any discrepancies from the actual ship in terms of dynamic responses should be quantified and subsequently accounted for in the overall assessment of navigational safety.

In the proposed digital testing guidelines, the well-established turning circle and zig-zag manoeuvres are adopted from [25]. These are selected to streamline the testing requirements as much as possible, given that at least part of the benchmark data would be available for existing ships. The digital model would be used to simulate these manoeuvres and the various values of longitudinal and lateral distances obtained from these manoeuvres would be compared against corresponding data representative of the actual ship. Possible sources for such data are:

i. Data from prior sea trials, which could be available if the autonomous ship being tested is converted from an existing conventional vessel. In this case, sea trials would have been conducted when the vessel was first delivered;
ii. Data from model tests; or
iii. Data from high-fidelity computational fluid dynamics simulations in which the actual hull form, propulsion and steering systems are modelled.

The turning circle manoeuvres should be carried out for both starboard and port turns in calm water, and for a range of rudder angles, similar to [25]. This would help ensure that the range of turning ability is captured. Similarly, the zig-zag manoeuvres should be carried out at different rudder angles.

5.1.1. Turning Circle Manoeuvres. To simulate the turning circle manoeuvres, the rudder deflection was set at three different rudder angles: 10°, 20° and 35°. The key information from the turning circle simulations that will be obtained and compared against benchmark data are advance, transfer and tactical diameter. Figure 2 illustrates the manoeuvre, as well as how these three values should be measured.

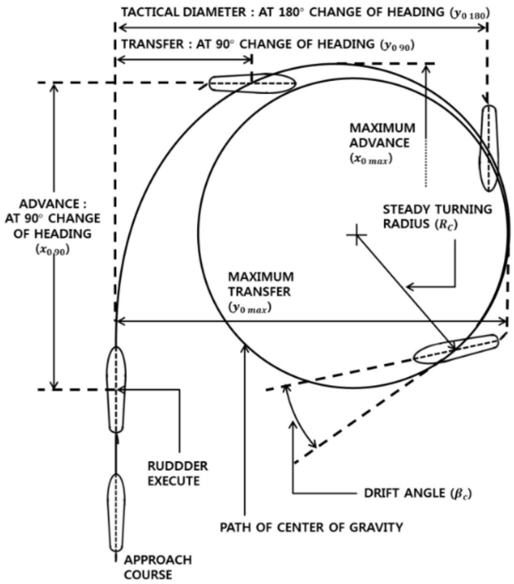

Figure 2. Turning circle manoeuvre from ITTC, 2017 [26]

5.1.2. Zig-zag Manoeuvres. To simulate the zig-zag manoeuvres, from a straight approach, the rudder will then be deflected at a specified degree angle and once the vessel has achieved this specified degree of course change, the rudder angle will be shifted to the opposite side.

The key data from the zig-zag test simulations are the longitudinal distance travelled from the start of the manoeuvre to the point where the ship is at the 2nd overshoot angle, and the maximum lateral displacement. This lateral displacement is the maximum perpendicular distance measured from the base course to the ship's zig-zag trajectory. By comparing these values obtained from the digital tests against benchmark data, the variability in longitudinal and lateral coursekeeping can be taken into consideration. The key information to be obtained from the zig-zag manoeuvres are illustrated in Figure 3.

5.2. Autonomous Navigation

Once the accuracy of the manoeuvring model relative to the actual ship is established, the digital model will be used to simulate autonomous navigation of the ship from one location to another and under various environmental conditions. This is to verify that the autonomous navigation algorithms would be able to steer the vessel along a safe course, with adequate control to account for the ship dynamics, environmental forces and any shallower bathymetry and fixed obstacles.

For an autonomous ship operating in Singapore port waters, it is recommended to apply the local environmental conditions for the autonomous navigation simulations. If the autonomous ship is designed for operations in other areas, environmental conditions corresponding to those areas should also be applied to ensure that the navigational algorithm is able to account for the resulting external environmental forces.

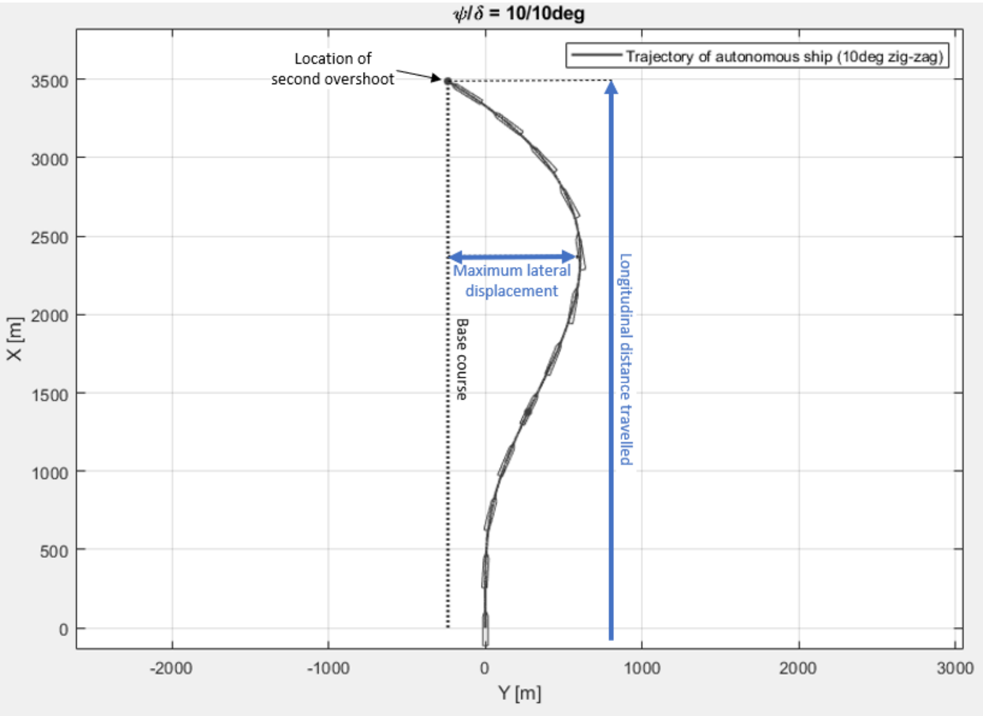

Figure 3. Key information to be obtained from zig-zag manoeuvres

Through our industry discussions, it is recognised that the autonomous navigational capabilities could be based on a diverse range of algorithms, some of which include uncertainty and scatter in terms of the predicted navigational course. It is thus prudent to assume that any numerical prediction of a physical system would include possible scatter within certain confidence limits. As such, it is recommended to undertake at least 30 repeats of each of the various combinations of autonomous navigational scenarios. This is based on the assumption that the scatter of the discrete points along a navigational course follows a Gaussian assumption, which is deemed to be reasonable, based on similar applications in other vessel collision models [27]. The scatter would be used to quantify the prediction interval, which can be calculated from the cross-track error (XTE) as follows:

$$Prediction\ interval_p = 3.983\left(XTE_p\sqrt{1+\frac{1}{30}}\right)$$

where the subscript p represents the combination of ship speed and draught condition being simulated. The value of 3.983 is used based on the assumption that the scatter in predictions can be modelled using a Gaussian assumption and corresponds to a sample size of 30.

By combining the prediction interval with the percentage difference between the digital model and benchmark data, the initial correction factor for the p combination of ship speed and draught can be obtained using the formula below:

$$u_p = prediction\ interval_p \times \Delta_{\max\,(p)}$$

Lastly, considering that vessels in the real-world environment would navigate in a range of speeds, the largest value of correction factor across the three ship speeds tested would be taken as the final correction factor at a given draught condition. The is expressed below:

$$u_{\mathrm{final}(d)} = \max\left(u_{6\ knots,d}\ , u_{12\ knots,d}, u_{90\%,d}\right)$$

where $u_{6knots(d)}, u_{12knots(d)}$ and $u_{90\%(d)}$ represent the initial correction factor at draught d for ship speeds at 6 knots, 12 knots, and at least 90% of the ship's speed at 85% of the maximum engine output, respectively.

5.3. Collision Detection & Avoidance

The third and final stage of the recommended digital testing guidelines aims to verify that the autonomous ship would be able to take COLREGS-compliant corrective actions and maintain a safe distance to avoid collision when encountering other vessel(s) in a seaway, where risk of collision exists. Various scenarios, derived, based on COLREGS, have been recommended for testing of the digital model. These scenarios comprise one - and two - vessel encounters and should be considered as the minimum level of testing. Tests with more than two vessels would help to further stress test the autonomous collision avoidance capabilities.

It is assumed that these tests are likely to be carried out prior to the certification or qualification of the sensor hardware systems and any sensor fusion algorithms required for the autonomous ship's situational awareness capabilities. As such, it is necessary to assume that the collision detection capabilities relating to the picking up target vessels is working as specified. Thus, if the range for collision detection is found to be lower than what was applied in the digital tests, the tests should be repeated using the new range.

Considering there is a possibility that some autonomous algorithms may have underlying probabilistic behaviour, resulting in multiple possible outcomes for each collision avoidance scenario, at least 5 simulations should be carried out using randomly generated heading angle(s) for the encountered vessels in each scenario.

5.3.1. Single Vessel Encounters

Rule 13 – Overtaking scenario, target ship. In this scenario, the autonomous ship should maintain course and speed and the target vessel, being the overtaking vessel, should be the vessel taking actions to allow safe passing. However, when it becomes apparent that the target vessel is not taking sufficient action, the autonomous ship shall take avoiding actions to pass clear with sufficient safety distance.

Rule 14 – Head-on Scenario with target vessel. Here the autonomous ship should alter course to starboard and pass port-to-port with sufficient safety distance. Noting that the COLREGS do not specify any heading angle values for the target vessel, the guidance provided in [28] has been adopted here, where the target vessel's course should be within "6° of being opposite (+/-180°)".

Rule 15 – Crossing Scenario with target vessel on starboard side. In this scenario, the autonomous ship should alter course to starboard and pass the target vessel from stern where practical with sufficient safety distance.

Rule 15 – Crossing Scenario with target vessel on port side. In this scenario, the autonomous ship should maintain course and speed until it becomes apparent that the target vessel is not taking action, the autonomous ship shall alter course to starboard, make a round-turn and pass clear with sufficient safety distance.

5.3.2. Two Vessel Encounters. In such multiple target vessel scenarios, the autonomous ship should assess the developing situation and risk of collision in accordance with appropriate COLREGS Rules. Avoiding action should be taken based on the prevailing circumstances. The evasive actions recommended herein are suggested manoeuvres – the autonomous ship could undertake different set of actions to pass safely.

One target vessel in head-on scenario & one target vessel approaching from starboard stern quarter. In this scenario, autonomous ship would assess the CPA and TCPA of the two target vessels and take avoiding action based on their course and speed. Sufficient safety distance should be kept relative to both target vessels.

Two target vessels in head-on scenario. In this scenario, the autonomous ship is required to make a bold alteration to starboard and pass port-to-port of both target vessels with sufficient safety distance both target vessels.

One target vessel in head-on scenario and one target vessel crossing on starboard side. In this scenario, the autonomous ship is required to alter course to starboard and pass both target vessels with sufficient safety distance.

One target vessel in head-on scenario and one target vessel crossing on port side. Here, the autonomous ship should assess the CPA and TCPA of the two target vessels and take avoiding action accordingly to maintain sufficient safety distance with both target vessels.

One target vessel crossing on starboard side and one target vessel overtaking from starboard stern quarter. Similar to the previous scenario, the autonomous ship should assess the CPA and TCPA of the two target vessels and take avoiding action accordingly to maintain sufficient safety distance with both target vessels.

One target vessel crossing on port side and one target vessel overtaking from starboard stern quarter. Here, the autonomous ship should maintain course and speed until when it becomes apparent that the target vessels are not taking action. The autonomous ship would then assess the CPA and TCPA of the two target vessels and take avoiding action accordingly to maintain sufficient safety distance with both target vessels.

One target vessel crossing on port side and one target vessel overtaking from port stern quarter. Similar to the previous scenario, the autonomous ship should maintain course and speed until it becomes apparent that the target vessels are not taking actions. The autonomous ship would then assess the CPA and TCPA of the two target vessels and take avoiding action accordingly to maintain sufficient safety distance relative to both target vessels.

One target vessel crossing on starboard side and one target vessel overtaking from port stern quarter. Here, the autonomous ship should alter course to starboard and pass with sufficient safety distance from both target vessels.

One target vessel in head-on scenario and one target vessel overtaking from port stern quarter. Similar to the previous scenario, the autonomous ship should alter course to starboard and pass with sufficient safety distance from both target vessels.

One target vessel overtaking from port stern quarter and one target vessel overtaking from starboard stern quarter. In this scenario, the autonomous ship should maintain course and speed until it becomes apparent that the target vessels are not taking actions. The autonomous ship would then assess the CPA and TCPA of the two target vessels and take avoiding action accordingly to maintain sufficient safety distance relative to both target vessels.

One target vessel crossing on starboard side and one target vessel crossing on port side. In this scenario, the autonomous ship should assess the CPA & TCPA of the two target vessels and take avoiding action accordingly to maintain sufficient safety distance with both target vessels.

5.4. CPA Corrections

For each of the 5 simulations carried out in this stage for each scenario and combination of draught conditions, an initial CPA value (represented as CPA_0) should be obtained as the initial safety distance. Recalling that the final correction factors (u_{final}) have been calculated from the outputs of Stages 1 and 2, to account for the prediction interval of the digital model, as well as the potential differences between the digital model and the actual ship, respectively. These correction factors are subtracted from CPA_0 to give the $CPA_{corrected}$ values for each draught, as per the equation below.

$$CPA_{corrected(d)} = CPA_{0(d)} - u_{final(d)}$$

For all scenarios, it is recommended that the $CPA_{corrected}$ should be at least 0.75NM, based on the findings of this study, as described in the earlier sections. In scenarios where the autonomous ship is unable to achieve this, such as in the unlikely scenario where the CPA of the autonomous ship relative to other obstacles or ships occur at the same time instant, the lowest $CPA_{corrected}$ value should not be less than 0.60 NM. An example of such a scenario is illustrated in Figure 4 below (not drawn to scale), where the autonomous ship is caught between an encountered vessel and another obstacle such that the CPA are attained at the same time instant. The figure also illustrates the relationships between CPA_0, the safety correction (u_{final}) and $CPA_{corrected}$.

5.5. Discussions and Limitations of Proposed Framework

To the authors knowledge, there are no standardised testing framework for assessment of an autonomous vessel's safety using digital means. In the existing practice, testing and assessment plans are jointly developed on a case-by-case basis by vessel developers and the certifying organisations, such as Class and / or Administrations. While this practice enables the development of a bespoke test plan that considers the high-level goals and associated risks to be addressed by each specific autonomous vessel to be certified, it does not facilitate comparison of the vessels' safety with other autonomous vessels nor existing vessels. This can hinder technological development efforts and safety level given that the requirement to be of "equivalent" safety level as existing vessels may not be determined in a consistent and transparent manner.

As noted earlier in this paper, autonomous maritime technologies are still undergoing active development. This means that what is considered as "ordinary practice of seamen" would change as the vessel demography shifts towards increasing level of autonomy. This is an important limitation of the proposed framework – whereby the testing framework will have to be reviewed from time to time to ensure relevant to the prevalent culture of the sea area being navigated. There are two aspects to this: firstly, the CPA values will have to be reviewed at regular intervals. This review will need to include not only AIS data and expert judgement from seafarers, navigational performance data from autonomous vessels will also need to be taken into consideration given the heterogeneous mix of vessel types. Updates of to the CPA values will help to ensure that the outcomes of collision avoidance manoeuvres (in the form of CPA) will be kept up-to-date as the overall level of vessel intelligence increases in a given sea area.

Another important limitation of the current framework relates to COLREG compliance – the encounter scenarios involving one vessel and two vessels have been laid out in a manner that reduces the subjectivity of interpretation. However, it is recognised that complex multi-vessel encounter situations may often require evasive actions that rely on the subjective aspects of COLREGS. In such situations, the appropriate actions to be undertaken will still have to be jointly established by the certifying organisation and the vessel developers. With the operationalisation of more autonomous vessels, information on the appropriate actions can be captured and used to derive metrics to ascertain the navigational safety of autonomous vessels in the future. Concurrently, with further evolution collision detection and avoidance technologies (e.g. from a combination of maritime, as well as from adjacent land-based transportation and robotics sectors), the future capabilities of autonomous vessels with regard to compliance of COLREGS would be enhanced, including in complex situations. This would prompt a further review of the proposed framework.

6. Conclusions

In this paper, a study has been carried out to develop a framework for digital testing of MASS navigation safety prior to sea trails. A review of the existing state-of-the-art, both in terms of technology developments and industry guidance in the form of publications from Classification Societies have been carried out. Based on the review and discussions with industry, a three step digital testing framework has been proposed, to first verify the accuracy of the digital model in representing the dynamic responses of the actual vessel, followed by tests to ascertain that the autonomous navigation algorithm is able to control (virtually) the vessel from one point to another, taking into account the real-world environment and lastly, that the autonomous navigation algorithm is able to carry out collision detection and avoidance.

Through the three stages, the framework takes into account any uncertainties in using the digital model to represent the actual autonomous vessel, potential scatter in terms of predicting a given navigation path, as well as the repeatability when carrying out collision avoidance actions. The subjective nature of COLREGS, as well as the need for a safety level that is equivalent to the existing situation with manned vessels is addressed through the use of CPA data to infer the safe outcomes of collision avoidance actions in Singapore Strait.

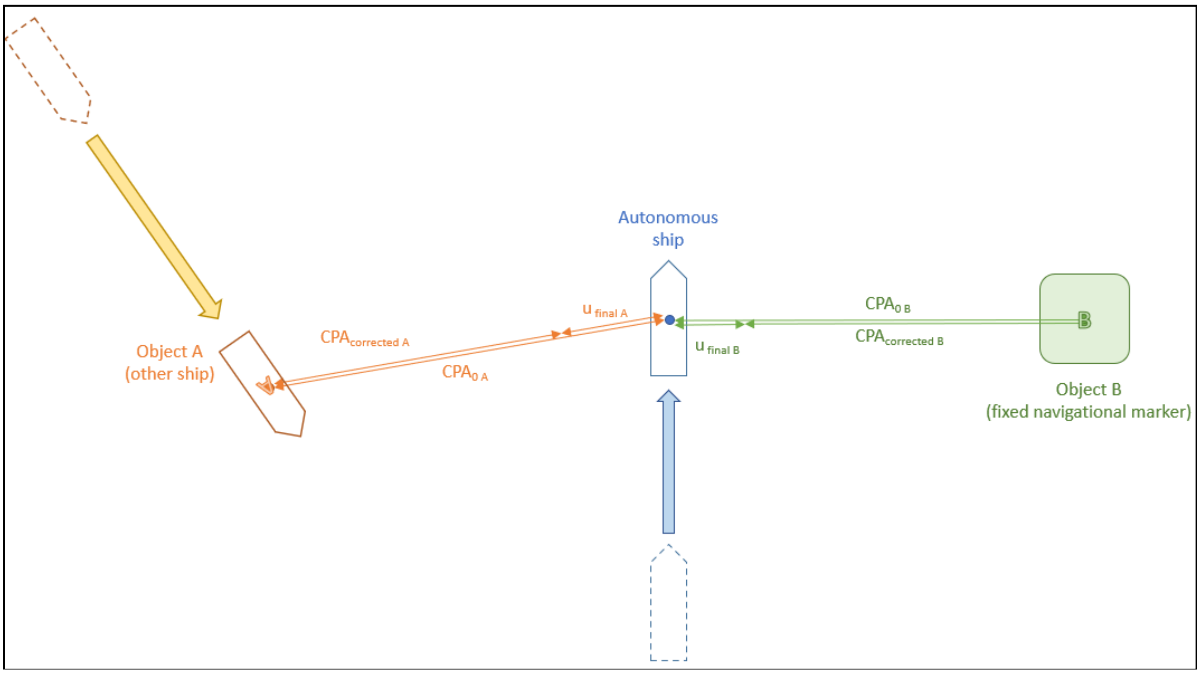

Figure 4. Illustration of the CPA_0, $CPA_{corrected}$ and u_{final} for a scenario where the CPA values of an autonomous ship relative to another ship, as well as a fixed navigational marker occurs at the same instant.

The proposed framework will provide a harmonised system for digital testing to reduce the likelihood of differing interpretations by different stakeholders, and concurrently, account for the need for a goal-based approach to testing.

Acknowledgements

This research is supported by the National Research Foundation, Singapore and the Singapore Maritime Institute under its Maritime Transformation Programme White Space Funding Support for the Establishment and Operation of the Centre of Excellence for Autonomous and Remotely Operated Vessels (CEAOPS), SMI-2019-MTP-01.

References

[1] Yara. (2020). Yara Birkeland press kit. https://www.yara.com/news-and-media/press-kits/yara-birkeland-press-kit [Accessed 17 Feb 22]
[2] Wärtsilä. (2020). Initial sea trials successfully completed by Wärtsilä & PSA Marine's ground-breaking 'IntelliTug' project. https://www.wartsila.com/media/news/13-03-2020-initial-sea-trials-successfully-completed-by-wartsila-psa-marine-s-ground-breaking-intellitug-project-2660851 [Accessed 17 Feb 22]
[3] ST Engineering. (2020). Sea Trials for Autonomous Tug Project https://onward.stengg.com/2020/04/29/sea-trials-for-autonomous-tugs [Accessed 17 Feb 22]
[4] Keppel Corp. (2019) https://www.kepcorp.com/en/media/media-releases-sgx-filings/keppel-to-develop-its-first-autonomous-vessel-for-operations-in-singapore-6564/ [Accessed 17 Feb 22]
[5] Ahmed, Y.A., & Hasegawa, K. (2016). Fuzzy Reasoned Waypoint Controller for Automatic Ship Guidance. IFAC, 49, 604-609.
[6] Jiang, Y., Zhang, S., & Yang, D. (2014). A Novel Position Estimation Method Based on Displacement Correction in AIS. Sensors. 14. 17376-17389. 10.3390/s140917376.
[7] Chen, D., Dai, C., Wan, X., and Mou, J. (2015). A research on AIS-based embedded system for ship collision avoidance, 2015 International Conference on Transportation Information and Safety (ICTIS), pp. 512-517.
[8] Goerlandt, F., Montewka, J., Kuzmin, V., & Kujala, P. (2015). A risk-informed ship collision alert system: Framework and application. Safety Science, 77, 182-204.
[9] Imazu, H. (2017). Evaluation method of collision risk by using true motion. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 11(1).
[10] Chircop, A. (2018). Testing International Legal Regimes: The Advent of Automated Commercial Vessels. The German Yearbook of International Law, 1-34.
[11] Rokseth, B., Haugen, O. I., & Utne, I. B. (2019). Safety verification for autonomous ships. In MATEC Web of Conferences (Vol. 273, p. 02002).
[12] Pedersen, T.A., Glomsrud, J.A. & Haugen, O.I. (2019). Towards Simulation-based Verification of Autonomous Navigation Systems. In: Proceedings of the International Seminar on Safety and Security of Autonomous Vessels (ISSAV) and European STAMP Workshop and Conference (ESWC).
[13] Hwang, Taewoong, and Ik-Hyun Youn. 2021. Navigation Situation Clustering Model of Human-Operated Ships for Maritime Autonomous Surface Ship Collision Avoidance Tests. Journal of Marine Science and Engineering 9, no. 12: 1458.
[14] Bolbot, V., & Theotokatos, G. (2021). Automatically generating collision scenarios for testing ship collision avoidance system using sampling techniques.
[15] Porathe, T. (2019) Maritime Autonomous Surface Ships (MASS) and the COLREGS: Do We Need Quantified Rules Or Is"the Ordinary Practice of Seamen" Specific Enough? TransNav, Int. Journal on Marine Navigation and Safety of Sea Transportation 13.3.
[16] ABS (2017a) Guidance Notes on Qualifying New Technologies. American Bureau of Shipping.
[17] ABS (2017b) Guidance Notes on Review and Approval of Novel Concepts. American Bureau of Shipping.
[18] ABS (2020) Guide for Smart Functions for Marine Vessels and Offshore Units. American Bureau of Shipping.
[19] BV (2020) Risk Based Qualification of New Technology – Methodological Guidelines, Bureau Veritas.
[20] BV (2019) Guidelines for Autonomous Shipping, Bureau Veritas.
[21] DNV (2013) Recommended Practice for Technology Qualification. DNV-RP-A203. DNV.
[22] DNVGL (2018) Class Guideline for Autonomous and remotely operated ships. CG-0264, DNVGL

[23] LR (2017a) LR Code for Unmanned Marine Systems. London: Lloyd's Register
[24] LR. (2017b). New code to certify unmanned vessels announced. https://www.lr.org/en/latest-news/new-code-to-certify-unmanned-vessels-announced/ [Accessed 17 Feb 22]
[25] IMO MSC Resolution MSC.137(76). Standards for Ship Manoeuvrability (2002) https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.137(76).pdf [Accessed 17 Feb 22]
[26] ITTC (2017). ITTC Quality System Manual Recommended Procedures and Guidelines Procedure Full Scale Manoeuvring Trial. Retrieved from: https://www.ittc.info/media/8179/75-04-02-01.pdf [Accessed 17 Feb 22]
[27] Pedersen, P.T., (1995). Collision and grounding mechanics. In: Proc. WEMT'95, Danish Society of Naval Architecture and Marine Engineering, Copenhagen, pp. 125–157.
[28] Cockcroft, A.N. and Lameijer, J.N.F. (2012). A Guide to the Collision Avoidance Rules (7th Edition), Butterworth-Heinmann, 2012