AUTONOMOUS VESSELS

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INTRODUCTION

Much progress has been made in the development of maritime autonomous technology in the last three years. Ongoing projects being held across the world trialing autonomous technology have progressed and new collaborations between stakeholders have been formed. In a step forward, the International Maritime Organization (IMO) has concluded the Maritime Autonomous Surface Ships (MASS) Regulatory Scoping Exercise.

The discourse on maritime autonomy has tended to view vessels in a uniform manner. However, this may not be suitable when addressing the unique characteristics of autonomous ships. The technological and regulatory challenges vary depending on vessel type and size.

Maritime UK has proposed classifying Maritime Autonomous Surface Ships into five categories:

Table 1 - Classes of MASS from Maritime Autonomous Surface Ship Systems (MASS) UK Industry Conduct Principles and Code of Practice [1]

Class of MASS	Characteristic	Notes
Ultra-light	Length overall <7m	*Derived from MCA High-Speed Craft Code where ∇ = moulded displacement, in m^3, of the craft corresponding to the design waterline
Light	Length overall ≥7m to <13m	
Small	Length overall ≥13m to <24m	
Large	Length ≥24m	
High-Speed	Operating speed V is not less than V = 7.19 ∇ 1/6 knots	

This categorization is helpful when discussing autonomous ships. Vessels with overall lengths of less than 24m typically do not comply with IMO regulations due to their size[2] and operations being typically limited to domestic or port waters only. The agility, use-cases (typically for surveillance and non-cargo carrying duties) and simpler machinery/equipment configuration of smaller vessels reduces the technological and regulatory complexity for the application of autonomous technology.

The risks, due to the technological and regulatory complexity increase for vessels classified as "Large" in the above-mentioned table. The focus of this paper is on "Large" vessels.

Autonomous development in the maritime sphere encompasses all aspects of ship design and operations. It also offers an opportunity for a total reset and rethinking of vessel design.

This paper provides an update on the efforts to develop regulations at the IMO and proposes the key main goal-based requirements for an autonomous vessel.

From the lessons learned from recent projects, the paper examines the pertinent issues in the implementation and operations of autonomous technology.

[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292155/hsc_2000_rev06-09_full-comp-all.pdf

[2] The International Convention for the Safety of Life at Sea, 1974 (SOLAS 1974) does not apply to cargo ships less than 500 gross tonnage. The International Convention for the Prevention of Pollution from Ships (MARPOL) does not apply to oil tankers less than 150 gross tonnage and other ships less than 400 gross tonnage.

UPDATES FROM THE IMO MASS REGULATORY SCOPING EXERCISE

A key activity in the development of regulations for autonomous operations was recently concluded in May 2021. However, this is by no means the end of this journey. Rather, the conclusion of the IMO Maritime Autonomous Surface Ships (MASS) Regulatory Scoping Exercise marks a step towards the drafting of requirements governing autonomous operations by the IMO.

BACKGROUND

Taking note of the pace of autonomous developments in the industry, the IMO recognized the need to be proactive crafting regulations for autonomous operations.

A proposal to undertake a Regulatory Scoping Exercise to determine how the safe, secure and environmentally sound operation of MASS might be introduced in IMO instruments was accepted at the 98th session of the Maritime Safety Committee meeting (MSC 98) in February 2017 [2].

To facilitate the process of the Regulatory Scoping Exercise, the degrees of autonomy were organized as follows:

Degree One: Ship with Automated Processes and Decision Support

- Seafarers on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.

Degree Two: Remotely Controlled Ship with Seafarers on Board

- The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.

Degree Three: Remotely Controlled Ships without Seafarers on Board

- The ship is controlled and operated from another location. There are no seafarers on board.

Degree Four: Fully Autonomous Ships

- The operating system of the ship is able to make decisions and determine actions by itself.

The Regulatory Scoping Exercise was carried out in two steps. At the first step, IMO instruments were reviewed to identify the instruments which are applicable to MASS and determine if the instrument needs to be amended or to be adapted to MASS operations.

The second step was conducted to analyze and determine the most appropriate way of addressing MASS operations. At this step, detailed discussions were held to determine if the existing instruments were required to be amended or new instruments need to be developed to address MASS operations.

The Regulatory Scoping Exercise was scheduled to be completed by the MSC 102 meeting in November 2020. However, due to the Covid-19 pandemic, conclusion of this scoping exercise was deferred, and the Regulatory Scoping Exercise was completed and finalized at the MSC 103 meeting in May 2021 [3].

IMO's Legal (LEG) and Facilitation (FAL) Committees are conducting separate Regulatory Scoping Exercises on the instruments under their purview. The Legal Committee has completed their scoping exercise whereas the scoping exercise for the Facilitation Committee is still underway and is expected to be completed in 2022 [4].

OUTCOME OF THE REGULATORY SCOPING EXERCISE

From the review of the various instruments under the purview of the Maritime Safety Committee (MSC), the scoping exercise identified a list of eleven (11) common potential gaps and/or themes which needs to be addressed to advance the development of regulations for autonomous operations [3].

The identified potential gaps and themes are as follows:

1. Meaning of the terms master, crew or responsible person
2. Remote control station/center
3. Remote operator as a seafarer

4. Provisions containing manual operations, alarms to the bridge
5. Provisions requiring actions by personnel (Fire, Spillage Cargo Management, onboard maintenance, etc.)
6. Certificates and manuals on board
7. Connectivity, cybersecurity
8. Watchkeeping
9. Implication of MASS in SAR (Search and Rescue)
10. Information to be available on board and required for the safe operation
11. Terminology

From this list, the IMO has identified four potential gaps and/or themes as high-priority issues that cut through critical IMO instruments and may require a policy decision or determination to progress further.

MEANING OF THE TERMS MASTER, CREW OR RESPONSIBLE PERSON

The possibility of fully autonomous and unmanned vessels has shone a spotlight on the critical role of the master, crew or responsible person on board vessels within the IMO regulations. The role of the master, crew or responsible person is alluded to and lies at the heart of many requirements. However, it is critical that their role is clearly defined and determined in order to develop requirements for autonomous operations.

REMOTE CONTROL STATION/CENTER

It is foreseeable that autonomous vessels and operations will be monitored or controlled from a remote control station/center which is likely to be located onshore. IMO has noted that this is a new concept for IMO instruments which require further in-depth study and deliberation.

REMOTE OPERATOR AS SEAFARER

In conjunction with the issue of a remote control station/center, questions have also been raised regarding the required qualifications, responsibilities and the role of a remote operator monitoring or controlling the autonomous vessel. Should IMO require that the remote operator be a qualified seafarer or should they be considered as a seafarer?

TERMINOLOGY

Maritime regulations at the IMO have developed organically over decades. Terminologies are defined in various instruments. However, there is no single repository. As autonomous development uniquely affects the whole spectrum of maritime regulations, a lack of agreed terminologies will be a potential source of confusion.

FUTURE WORK

Upon the conclusion of the Regulatory Scoping Exercise, the IMO has agreed that they should embark on plans to develop requirements for autonomous operations with the target of publishing these requirements by 2025.

The IMO has not ruled out the publishing of interim guidelines before the requirements are published in 2025, in addition to Interim Guidelines for MASS Trials already published on June 14, 2019 (MSC.1/Circ.1604).

GOAL-BASED FRAMEWORK FOR AUTONOMOUS VESSELS

To allow operations of fully autonomous vessels, the maritime industry requires regulations for the design of autonomous vessels. As noted above, this is an ongoing endeavor from the IMO. This white paper proposes a goal-based framework constructed from the ground-up for application to fully autonomous vessels.

The intent of the requirements contained in key regulations applicable to ship-design have been examined, namely the:

- International Convention for the Safety of Life at Sea (SOLAS, 1974, as amended), and
- International Convention for the Prevention of Pollution from Ships (MARPOL).

From this study, we have identified the following high-level safety goals.

1. Maintain propulsion
2. Maintain safety of vessel
3. Protect against flooding
4. Maintain safety of navigation
5. Communicate distress
6. Meet environmental concerns
7. Provide continuous monitoring and situational awareness
8. Maintain command and decision system
9. Maintain safety of cargo

Additionally, a fully autonomous vessel is required to meet the following goal:

10. Maintain communication with remote operations center

MAINTAIN PROPULSION

The first goal is that the vessel be able to maintain its means of propulsion at all times. In the event of loss of propulsion, the vessel should be able to quickly restart the propulsion plant without external aid.

To achieve this goal, the propulsion system and supporting auxiliaries are to be designed, constructed and equipped to provide:

- Continuity of electrical power, and
- Robust, reliable, or redundant propulsion systems.

MAINTAIN SAFETY OF THE VESSEL

The goal of maintaining safety of the vessel has to be viewed multi-dimensionally as follows:

Maintain Continuity of Electrical Power

- Continuity of onboard electrical power is critical to safeguard the operation of propulsion auxiliaries, control and communication systems. The vessel's electrical power generation and distribution should be designed to be robust and reliable. Where necessary, redundant power systems are to be considered.

Manage Fire Risk

- For a fully autonomous vessel without onboard personnel, the fire protection concept for the vessel will have to depart from current conventional concepts and be redesigned. Current regulations for conventional ships take into account the presence of seafarers onboard to assist in fire-fighting efforts. However, where there are no onboard personnel, the existing fire protection philosophy will have to be reexamined and redefined.

Manage Onboard Machinery

- Without onboard personnel to attend to machinery failures, onboard machinery and systems have to be designed to be robust and reliable. There will be increased emphasis on machinery health monitoring to anticipate and resolve issues before they surface. For critical machinery, redundancy may have to be built into the design.

Prevent Unauthorized Access or Boarding of the Vessel

- This concern will take on added importance for fully autonomous vessels without onboard personnel. The vessel will have to be designed to prevent unauthorized access or boarding of the vessel.

PROTECT AGAINST FLOODING

Water ingress and flooding is a key concern of vessel safety. The following areas are to be addressed:

Bilge System and Operation of Sea Valves

- Operation of these systems will need to be highly automated or autonomous to deal with water that may accumulate within the vessel and to ensure that the hull is not breached in any compartment.

Ventilation Openings

- Ventilation openings in vessels are necessary for the safe operation of machinery and for human habitability purposes. In the design of autonomous vessels, the number of ventilation openings may have to be reconsidered. Although it might appear that ventilation openings for some spaces might not be required due to the lack of human presence onboard autonomous vessels, the design should take into consideration human presence during maintenance or inspection of the vessel.

Ventilation openings are also ingress points for seawater. The closing or opening mechanism for ventilation openings may need to be automated and monitored.

MAINTAIN SAFETY OF NAVIGATION

The goal of maintaining safety of navigation of the vessel requires analysis of not only the vessel's own onboard systems but also the vessel's interaction with other vessels and the ship's response to environmental and sea conditions.

To achieve this goal, the vessel is to be able to:

- Maintain steering capability in the event of a failure
- Navigate in accordance with Convention on the International Regulations for Preventing Collisions at Sea (COLREG, 1972 as amended) principles

- Continuously communicate its intent to surrounding vessels in accordance with COLREG principles and local requirements
- Receive and understand communications from surrounding vessels
- Monitor environmental conditions
- Communicate navigational distress to surrounding vessels

COMMUNICATE DISTRESS

In the event the autonomous vessel finds itself in an emergency or distress situation, the vessel is to be able to communicate its distress to others including:

- Its own remote operator or control center
- Nearby vessels
- The relevant port or coastal state authorities

This is to enable the responsible parties to respond rapidly to protect the asset and to alert surrounding vessels so that they may be aware and minimize the possibility of a collision.

Situations in which it is to communicate distress include:

- Loss of propulsion or restricted maneuvering
- Failure of protection against flooding (i.e. when it is taking in water)
- Fire
- Loss of navigation capability
- Loss of communication with shore control station

MEET ENVIRONMENTAL CONCERNS

The environmental impact of autonomous vessels should not be disregarded. As such, an autonomous vessel is also to meet the goal of being compliant with the intent of the requirements contained in the MARPOL. This will include requirements contained in:

- MARPOL Annex I (Regulations for the prevention of pollution by oil)
- MARPOL Annex IV (Regulations for the prevention of pollution by sewage from ships)

For the purpose of this paper, it is assumed that the fully autonomous vessel will not carry cargoes covered by MARPOL Annex II (noxious liquid substances in bulk) and MARPOL Annex III (harmful substances in packaged form).

In addition to MARPOL Annex I and Annex IV, the autonomous vessel is also to be able to comply with local Flag or Port State requirements pertaining to prevention of pollution.

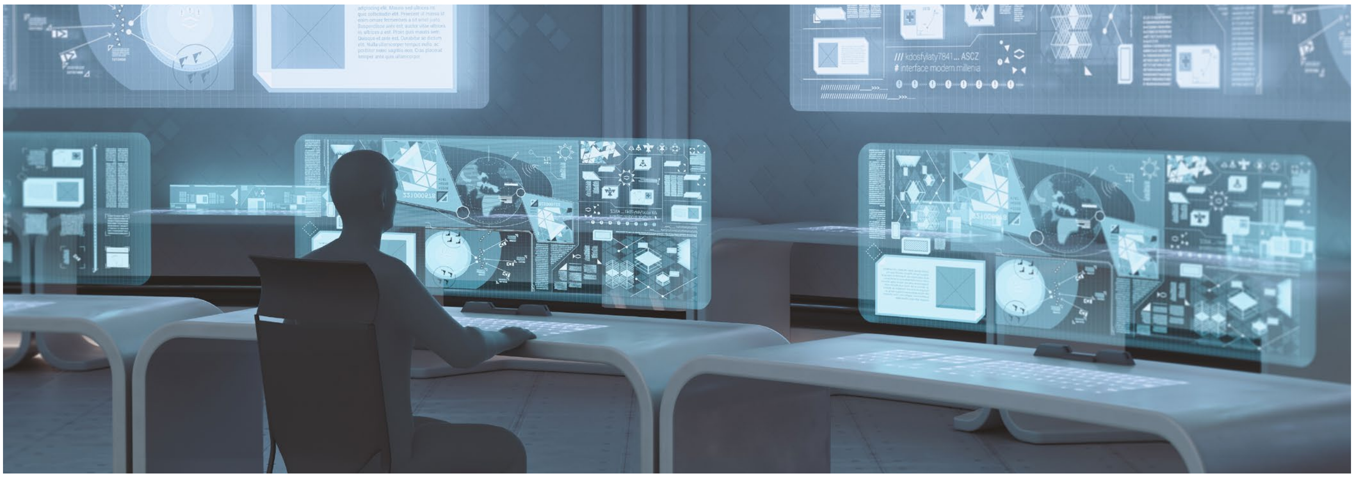
A reporting procedure is also to be established for the fully autonomous vessel to meet submittal requirements for Regulatory Compliance.

CONTINUOUS MONITORING AND SITUATIONAL AWARENESS

Without onboard personnel to monitor and care for the vessel's machinery, continuous monitoring and situational awareness capabilities will be critical for autonomous vessels. These capabilities will enable the autonomous vessel to perform its tasks and to inform the remote operators on the condition of the vessel and key systems.

At the minimum, the following are to be continuously monitored:

- Propulsion and electrical power generation and distribution systems
- Safety/damage control
- Stability and ballast control (intact and damaged)



- Structural integrity and health
- Navigation and position (geolocation)
- Environmental regulatory reporting
- Normal operations and restorative actions
- Cybersecurity

MAINTAIN COMMAND AND DECISION

The most critical system onboard an autonomous vessel will be its central command and decision system. It performs the critical functions of:

- Observing and analyzing its surroundings
- Making decisions
- Carrying those decisions out and giving instructions to various constituent systems
- Communicating with the remote operator station

As such, the continued and proper operation of the central command and decision system will be key for the vessel's safe operation.

Three critical factors are essential in the design of the central command and decision system:

- Redundancy
- Reliability
- Cyber security

MAINTAIN SAFETY OF CARGO

The autonomous vessel is to be able to maintain the safety of the cargo which it is carrying. Cargo is to be stored and secured in such a way that the vessel and the environment are not put at risk. Depending on the cargo being carried, means to monitor the cargo may also be required.

MAINTAIN COMMUNICATION WITH REMOTE OPERATIONS CENTER

For vessel supervision and safety management it is critical for the vessel to always maintain communication with the shore control station.

Additionally, the vessel should be capable of communicating with other vessel traffic, pilots, harbor control and riding crews or transport team.

For fully autonomous and unmanned vessels, external parties may have to communicate with the remote operators located at the remote operations center.

KEY ISSUES TO RESOLVE/CONSIDER

REMOTE OPERATOR STATION

It is foreseeable that autonomous and remote controlled vessels will be monitored or controlled from a remote operator station. This is a new concept in marine and offshore operations and the issues and considerations surrounding it needs to be examined.

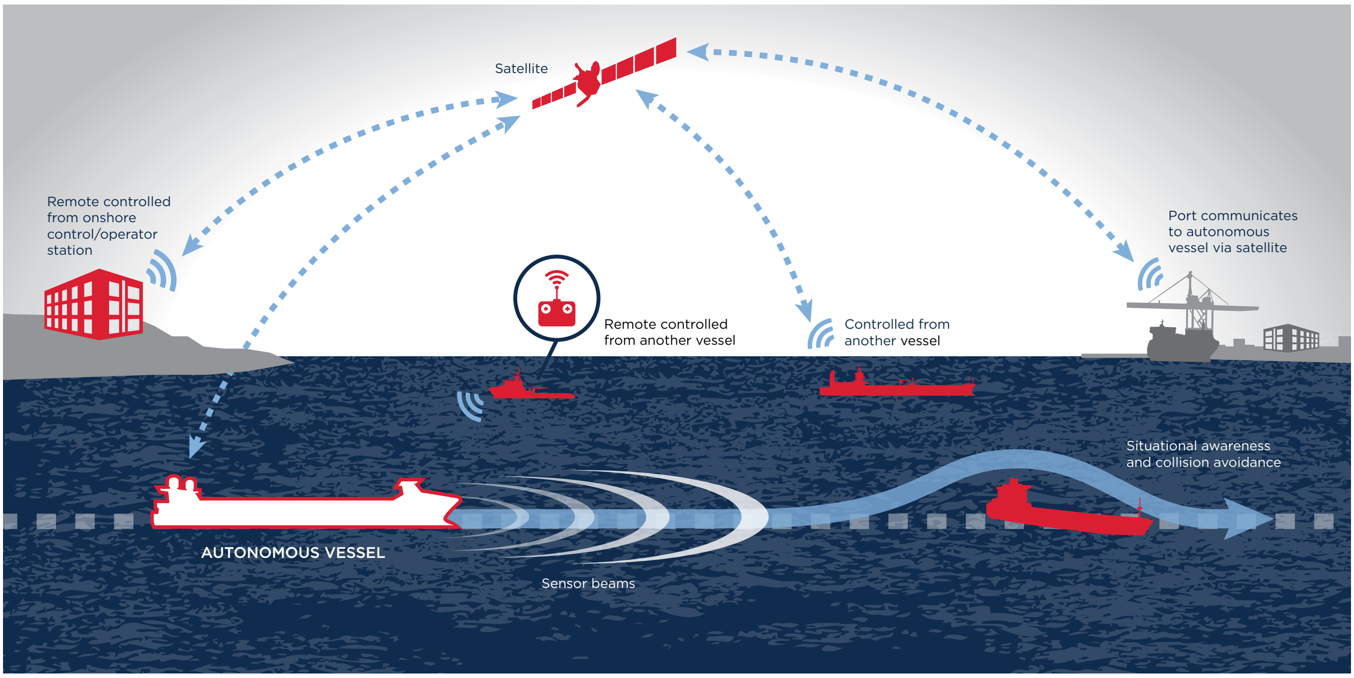


Figure 1 – Autonomous and remote controlled operation landscape

The following are some of the foreseeable roles of a remote operator station [5]:

- Voyage planning of all aspects of the autonomous vessel for example setting of navigation waypoints and the configuration of the vessel's machinery
- Monitoring the progress of the voyage
- Maintaining situational awareness
- Health monitoring of onboard machinery and vessel's hull/structure
- Responding to anomalous and emergency situations
- Communicating with and sharing information with ports or coastal states when in their waters, for example liaising with a port's VTS (Vessel Traffic Service) system
- Communicating with surrounding vessels
- Controlling transitions between operating modes

There are various possible configurations for remote operations. A remote control or operator station could be located onshore or on another vessel. There is also the possibility of a remote control/operator station monitoring and controlling multiple vessels.

TECHNOLOGY

Communication and Connectivity

- Continuous and reliable communication and connectivity between the autonomous vessel and the remote operator station is a key enabler.
- The communication will need to be bidirectional, accurate, scalable, and supported by multiple systems – creating redundancy and minimizing risk. Reliability of the communication channel between the vessel and remote control or operator station is crucial to safe operations.

Augmented reality (AR) technology

- With operators away from the vessel, the situational awareness of the operator will be reduced. A key concern from stakeholders and regulators is: will this reduced situational awareness have any adverse impact on safety of operations? What is the minimum required level of situational awareness a remote operator should be provided in order to attain an equivalent level of safety and operational efficiency?
- Against this backdrop, AR technology will be useful in assisting to bridge the gap between perception and reality.
- AR is a technology that allows the superimposition of digital contents (images, sounds, text) over a real-world environment.
- AR has started to be utilized in this field. For example, AR combined with cellular network connectivity allowed operators at a remote-control center to monitor and guide the operations of a tug remotely [6].

SKILLS AND COMPETENCE

The remote operator will be at the core of remote control/operator station operations. Their skills and competence will be an important factor in supporting safe autonomous and/or remote-controlled operations. Currently, the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) Convention sets precise requirements for education, training and experience (sea service) for personnel working on-board vessels. For shore personnel and management of vessels, the International Safety Management (ISM) Code provides requirements for the safe management and operation of ships [7].

Saha (2021) identified three key competences necessary to be developed to perform the role of future remote operators:

- System understanding
- Communicational and technical knowledge
- Maritime competence.

Knowledge of regulations, navigational competence, and engineering was also found to be necessary (see Figure 6). Further, the data analysis suggests:

- Extended use of simulator on training and education followed by a trainee period can prepare the future remote operator effectively
- Experienced OOW (Officer of the Watch) was preferred as a future remote operator, for the initial phases [7].

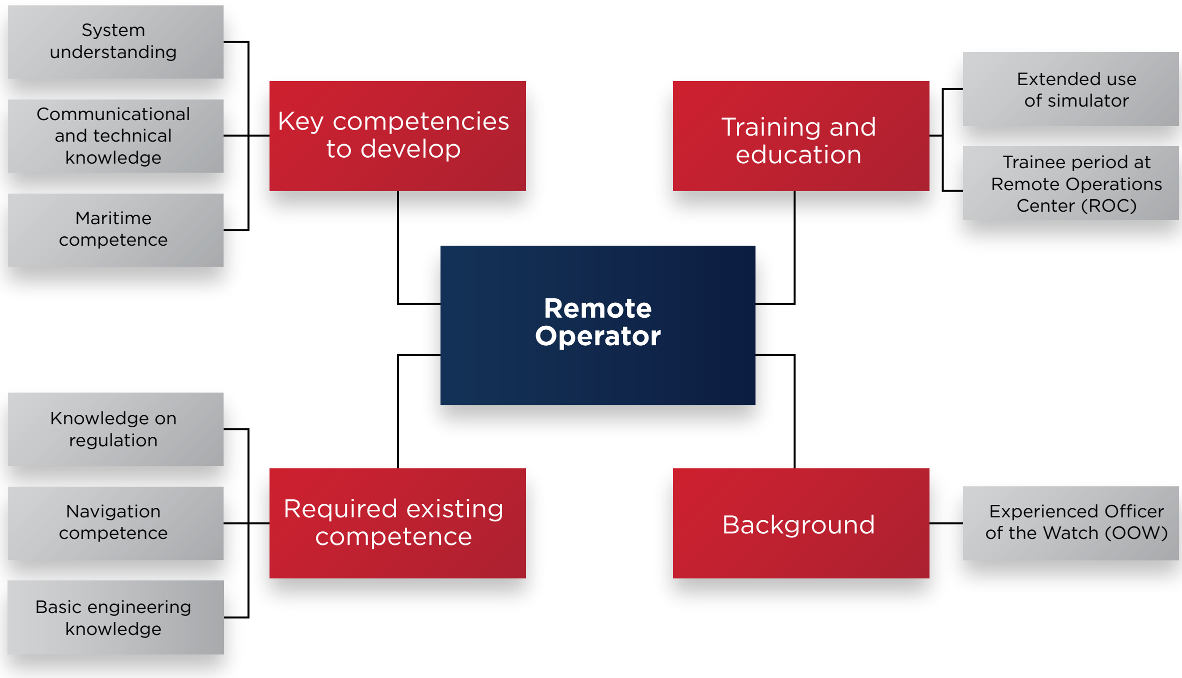


Figure 2 - Competence Map for Remote Operator [7]

Further research and development of the required skills and competency of remote operators is required. Presently, considering that seafarers have most of the requisite skills and experience of ship operations, it is likely that the first remote operators will be seafarers. Gaps between current skillsets and future required knowledge skills will need to be scoped out in order to upskill current seafarers for this and other new jobs arising from autonomous and remote control operations.

CONNECTIVITY

The connectivity between the vessel and the remote station that performs monitoring and control is essential to autonomous and remote-control functions, and there are various factors to be considered, such as the bandwidth, data integrity, reliability, and latency. Data integrity should be verified and corrupted or invalid data should have timely recovery. Data connection to the vessel should be robust and fault resilient. For autonomous or remote-control functions of higher risk, the functions are not to be compromised even with degradation of network or complete loss of connection. Network latency should satisfy the functional and performance needs of the specific autonomous or remote-control function.

There are two major communication methods, namely through cellular network and through satellite network, for coastal and deep ocean services, respectively. They differ from each other in various ways.

Cellular network relies on base stations to provide communications coverage. Therefore, its range is limited to the availability of base stations, and hence can only connect to vessels close to the shore. Satellite network, on the contrary, has no such limitation. With combination of satellite constellations and ground stations, satellite network can reach across the globe, and therefore is the only option to connect to vessels far from shore.

Though cellular networks suffer from distance limitation, its latency is usually lower than satellite network because for the satellite network, transmissions must travel a vast amount of distance from the satellite to the vessel. Satellites on higher orbits have higher latency than those on lower orbits [8].

For autonomous vessel use, data exchange volumes larger than typical navigation needs is required for status and operational monitoring and operation purpose. The communication equipment should also have enough data capacity to satisfy the functional and performance requirements. The amount of data that can be carried depends on the frequency band of the network. The higher the frequency, the more data can be carried. The most common cellular network right now is the "Long Term Evolution" (LTE) network, which is close to but not a true 4G network [9]. The frequency band is from around 450 Mhz to 5 GHz. The 5G network, which is the next generation communication protocol, has a low band from around 410 MHz to 7 GHz and a high band from around 24.25 GHz to 52.6 GHz [10].

As for the frequency bands of satellite networks, it can be as low as 1 GHz on the L band, higher at 12 GHz on the Ku band, and even higher at 27 GHz on the Ka band [11], which is on a similar frequency range as the 5G cellular network.

The implementation should also consider the connection speed and whether the performance would be significantly affected by environmental conditions and marine traffic. The cellular network and satellite network can reach similar speed, but satellite network usually costs higher. Bandwidth is also dependent on the number of vessels or other bandwidth consumers in a certain coverage area, such as near a busy port. Slow data speed in congested area can be improved with better infrastructure for cellular network and more satellites for the satellite network.

The advent of 5G cellular technology has created interesting possibilities for autonomous and remote control operations. With speeds of up to ten gigabits per second, 5G has the potential to be up to 100 times faster than 4G. Its latency rate is also significantly lower at just 1 millisecond as compared to the latency for 4G which is around 200 milliseconds. [12] This is useful for the development of autonomous and remote control technology as with increased sensors, the quantity of data flowing between ship and shore is expected to increase. Low latency will also be critical in the control of machinery. However, the drawback for 5G cellular technology is that the coverage area will be smaller than 4G technology. 5G technology is based on super-high frequency airwaves and these airwaves do not travel very far. [13] A huge amount of investment in base stations are required to establish 5G networks and this may be difficult to be implemented in port waters. Nonetheless, it may be possible to utilize local mobile ad-hoc 5G networks between vessels close to each other to enable fast exchange of data between each other. [14]

MANNING

The optimization (or in some cases, elimination) of manning onboard vessels is one of the key drivers for autonomous development and yet, it is also potentially the most challenging issue [15].

The United Nations Convention on the Law of the Sea (UNCLOS) article 94(4)(b) requires all ships to be "in charge of a master and officers who possess appropriate qualifications". SOLAS, MARPOL, STCW and various other regulations presumes that a master will be present onboard and the ship manned [15] [16].

Societal acceptance to unmanned operations and the possible loss or reassignment of traditional seafarer jobs is also critical to this discussion. Some key maritime stakeholders have raised concerns on the impact of autonomous ship operations on port operations and the possibility of job losses [17].

The legal, regulatory and societal challenges which autonomous technology needs to surmount will take some time. In the meantime, smart and autonomous technology has arrived and the focus is to ensure that these technologies be implemented safely.

SIMULATION TESTING

Software underpins the delivery of autonomous and remote control functions. To deliver these functions as intended and safely, software quality and reliability are crucial. In addition, the underlying algorithms may not be understandable and directly verifiable. There are many questions about the validation of software and algorithms used in advanced automation, autonomous and remote control functions, such as: How do we define reliability? How do we track and evaluate decisions taken by software? How do we supervise correct behavior to achieve trust and control learning? How do we define liability in the event of software failure?

The failure of autonomous and remote control functions can have a serious impact on their mission, performance, or safety. Thus, they should be thoroughly tested and verified to prevent potential failures, covering comprehensive, diverse and critical situations for both normal and abnormal operational conditions.

Traditional validation methods are typically costly, time-consuming, limited in the reproducible scenarios, and risky in case of non-acceptable behaviors.

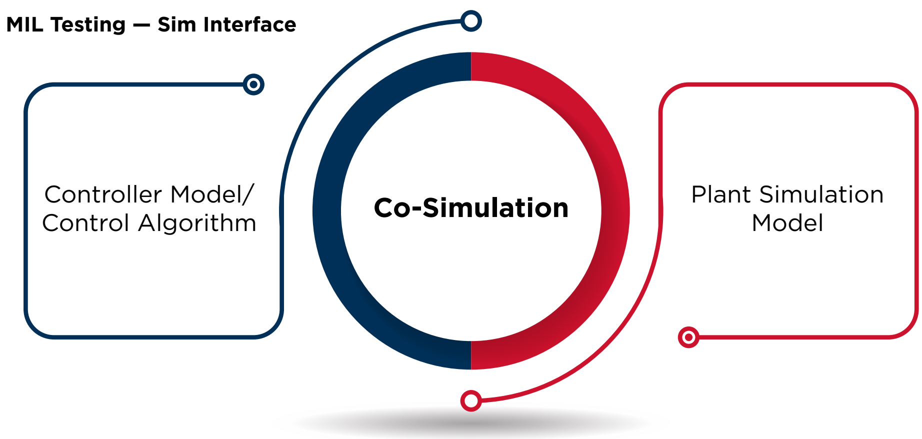
To improve reliability and to avoid catastrophic failures, software can be tested using system-level pre-validation that is done in virtual worlds through simulation, to discover faults and fix them before deployment.

Model-in-the-Loop (MIL), Software-in-the-Loop (SIL) and Hardware-in-the-loop (HIL) simulation techniques, which are approaches that have been widely used in Model-Based Design (MBD) in the Aerospace, Military and Automotive Industries can be leveraged for autonomous and remote control functions.

MODEL-IN-THE-LOOP (MIL) SIMULATION

MIL testing is intended for verification of the control algorithms logic and ensuring the satisfaction of their requirements. At this level, a model for the controller and a model for the plant are created in the same simulation space. The controller and plant models are independent of each other. The interaction between these two models take place via a co-simulation algorithm. The co-simulation algorithm regulates their interactions and time synchronization. The MIL simulation and testing is performed entirely in a virtual environment and without any need for any physical component. The focus of MIL testing is to verify the control algorithm, and to ensure that the interactions between the controller and the plant meet the system requirements. Benefits of MIL:

1. MIL allows testing at early stages of the development cycle.
2. A newly designed system can be tested even if some parts have yet to be physically realized – these parts are simulated instead.
3. The characteristics of the simulated system can be varied to represent alternative configurations – this is more convenient than changing physical components.

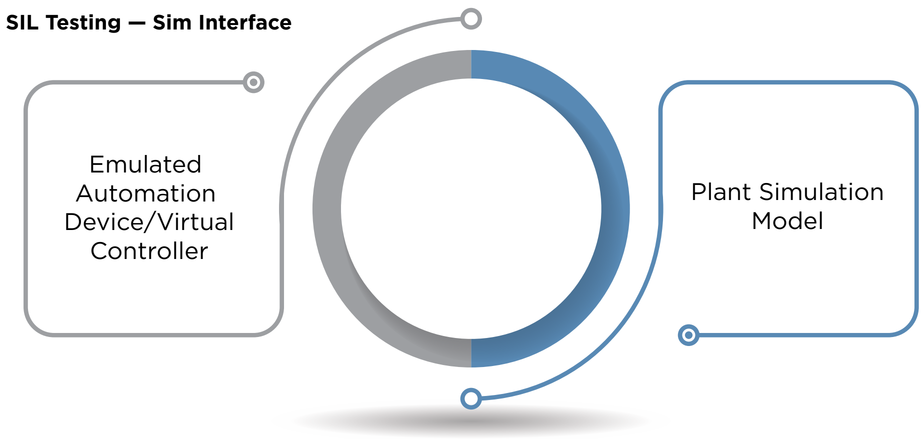


SOFTWARE-IN-THE-LOOP (SIL) SIMULATION

The testing at the SIL-level is performed in a virtual and simulated environment similar to MIL, but the focus is on controller code which can run on the target platform. In SIL, virtual (emulated) controllers are used to simulate the actual hardware.

Benefits of SIL

1. Virtual validation of control strategies, without putting lives or machinery at risk, but using the real controller code.
2. Cost reduction, by troubleshooting errors early on in the design process.
3. Using "virtual time" capabilities, i.e. slowing-down or accelerating the time, which can be very helpful in troubleshooting failures or to simulate real processes that may take hours quickly in minutes or seconds.

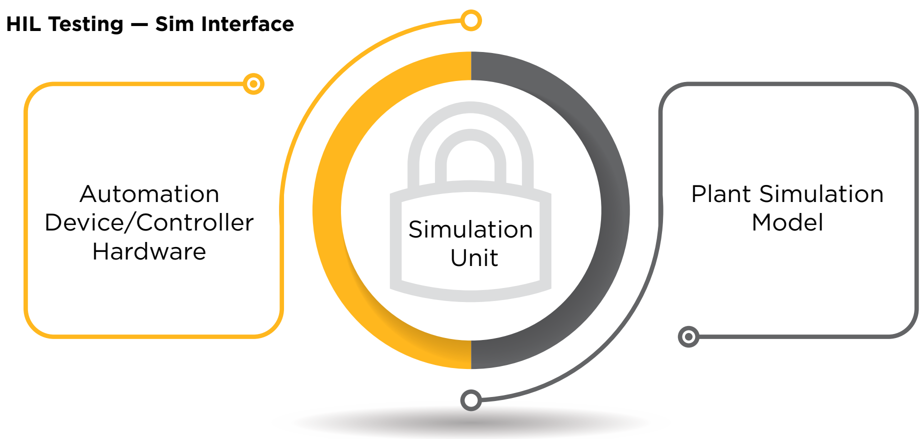


HARDWARE-IN-THE-LOOP (HIL) SIMULATION

The main objective of HIL is to verify the integration of hardware and software in a realistic environment. At this level, the controller software is fully installed into the final control system. The plant is either a real piece of hardware or is some software that runs on a real-time computer with physical signal simulation to lead the controller into believing that it is being used on a real plant. The controller software is connected to the plant simulation model via a hardware device called a simulation unit.

Benefits of HIL

1. Validate controller logic strategies online based on a virtualized controlled system.
2. Enhance or compare data measured from the field with simulated data.
3. Simulated predictions through a system digital twin model, fed with real data acquired from the field.



MODELING AND SIMULATION SOFTWARE

Modeling the plant models and controls system models has been widely used in the Model-Based Design (MBD) in the Aerospace, Military and Automotive Industries. Multiple commercially available tools/software supporting this are available.

CYBERSECURITY

Existing ships and offshore units are equipped with high degrees of automation. In recent years, the industry has expanded its safety focus beyond the traditional hull, mechanical and electrical areas to cover software and cybersecurity. Safety of operations is heavily dependent on the software operating as it is designed and the vessel's operational technology (OT) systems being free from external interference (malicious or not).

The availability and necessity for autonomous and remote control operations to be in constant communication via satellite or cellular communications greatly increases the cyber vulnerability of the ship or offshore unit.

Cybersecurity can no longer be considered on the periphery of autonomous discussions but it has to sit at the core of it.

Due to the repercussions of a cyber incident, cybersecurity is now front and center of maritime stakeholders' concerns. A holistic view on cybersecurity covering the entire ecosystem enabling autonomous and remote control operations is required i.e. from a vessel's onboard systems, communication systems, remote control/operator station systems, human operators and other interfacing systems such as a Port Vessel Traffic Systems (VTS) and other service provider.

ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML)

Artificial Intelligence (AI) is a technology for creating intelligent systems that can simulate human intelligence. Machine Learning (ML) is a subfield of AI, which enables machines to learn from past historical data without being explicitly programmed. Artificial intelligence and machine learning techniques are increasingly being used in smart and autonomous functions.

For example, different regression algorithms have been used for the prediction of a ship's operational parameters, such as the required main engine power [18]; deep learning has been used for ship recognition and tracking [19]; reinforcement learning (RL) and neural networks (NN) have been used for ship's path planning and optimization [20].

The pre-processing of the data set that will be imported to the ML algorithms is a crucial step for ML. ML requires high-quality data. Thus, a suitable data and Internet-of-Things (IoT) architecture which defines and facilitates clear processes for collecting data from different sources, filtering, standardizing, pre-processing and merging data in a common platform and checking its quality is often necessary [21].

Even though Machine Learning is known to succeed in vaguely defined problem domains, AI software may contain faults introduced during the learning process of a neural network [20]. As an example, Katz has analyzed the deep neural network implementation of the next-generation airborne collision avoidance system for unmanned aircraft and found that several logical requirements did not hold for the system as well as some adversarial perturbations that could lead to erroneous collision avoidance actions [22]. As such, this is an important area which the industry should pay attention to and work towards crafting a verification and validation framework for artificial intelligence and machine learning techniques.

STATUTORY CONSIDERATIONS

In the absence of international regulations for autonomous vessel design and operations, Flag Administrations and Port Authorities have proposed frameworks and guidelines to allow trials for autonomous technology in their waters [23] [24].

In addition to the Interim Guidelines for MASS Trials (IMO MSC.1/Circ.1604), Flag Administrations are relying on the IMO Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments (IMO MSC.1/Circ.1455) [24]. Ship owners / operators intending to utilize autonomous technology in lieu of complying with IMO requirements may be required to prove that the alternative method complies with the intent of the requirements in accordance with the aforementioned Guidelines.

CONCLUSION

Discussions surrounding autonomous developments are starting to take on a practical shape. Various projects to understand and propose solutions to enable practical use and implementation of autonomous technology have been completed and some are still ongoing. Nonetheless, the industry is facing up to the intricate challenges and obstacles which have to be overcome.

The conclusion of the MASS Regulatory Scoping Exercise at the IMO and subsequent efforts to map out the way forward to drafting international regulations is a good progress. While there are significant challenges ahead, this is a good sign that the industry sees value in autonomous technology and that it has the potential to bring improvement to maritime operations and safety.

As the industry endeavors to develop regulations and requirements for autonomous vessel design and operations, this paper has proposed a goal-based framework based on the intent of the requirements contained in current conventional regulations. This leverages on the wealth of experience which formed the basis of these regulations. From ongoing autonomous technology trials and projects, some key issues have surfaced. Some of these issues pertain to the difficulty for autonomous vessels to meet current requirements whereas some issues are new to the maritime industry. To allow the adoption of autonomous technology and operations, regulations being planned for autonomous vessel design and operations will have to address these issues.

ABS SUPPORT

The ABS *Guide for Autonomous and Remote Control Functions*, published in July 2021, provides a mix of goal-based and prescriptive requirements set against a wider risk-based framework to guide the implementation of autonomous and remote control functions on marine vessels and offshore units.

ABS is equipped to assist owners, operators, shipbuilders, designers and vendors in the verification and validation of autonomous vessels utilizing the principles in the above-mentioned Guide along with the ABS *Guidance Notes on Qualifying New Technologies* and the *Guidance Notes on Review and Approval of Novel Concepts*.

APPENDIX I – REFERENCES

ABS PUBLICATIONS

ABS *Advisory on Autonomous Functionality*

ABS *Guide for Autonomous and Remote Control Functions*

ABS *Guide for Smart Functions for Marine Vessels and Offshore Units*

ABS Whitepaper – *Reduced Manning on Offshore Facilities*

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APPENDIX II – ACRONYMS

AI	Artificial Intelligence
AR	Augmented Reality
FAL	Facilitation Committee
COLREG	Convention on the International Regulations for Preventing Collisions at Sea, 1972
HIL	Hardware-in-the-Loop
IMO	International Maritime Organization
ISM	The International Safety Management Code
LEG	Legal Committee
LTE	Long Term Evolution
MASS	Maritime Autonomous Surface Ships
MARPOL	International Convention for the Prevention of Pollution from Ships
MBD	Model-Based Design
MCA	Maritime and Coastguard Agency, United Kingdom
MIL	Model-in-the-Loop
ML	Machine Learning
MSC	Maritime Safety Committee
NN	Neural Networks
OOW	Officer of the Watch
OT	Operational Technology
PLC	Programmable Logic Controller
UNCLOS	United Nations Convention on the Law of the Sea
SAR	Search and Rescue
SIL	Software-in-the-Loop
SOLAS	International Convention for the Safety of Life at Sea
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
VTS	Vessel Traffic Service

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