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REMOTE-CONTROLLED AND AUTONOMOUS SHIPS

IN THE MARITIME INDUSTRY

SAFER, SMARTER, GREENER

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1 POSITION

A modern ship today includes complex automated systems. This technological development has allowed for a gradual reduction in crew. Increased data collection, processing and interconnectivity capabilities, enabling the automated systems to be controlled remotely or by algorithms, may gradually further reduce manning and even result in unmanned ships. This has the potential to increase safety, improve the environmental performance of and enable more cost-effective shipping. The technologies for this are rapidly becoming available, but at this stage it is questionable whether their implementation would ensure the safe operation of a ship.

Currently, there are few showstoppers for more automation in international regulations. However, this is not the case for a reduction in manning. In such a case, the technology replacing manning needs to outperform the crew in terms of safety, efficiency and environmental protection, and amendments or new regulations will be required. DNV GL believes this could be achieved by developing goal-based statutory requirements for such systems, issued by the proper authorities. It should then be left to classification societies to develop specific technical requirements and verification methodologies which establish satisfactory evidence that the statutory requirements are met. In order for stakeholders to obtain the necessary confidence that required safety levels are met, DNV GL will, in its role of class, establish procedures to ensure that the proper processes have been used to develop the product and to verify the safety of the product itself. Verifying the safety of the product will be particularly demanding, but failure to do so will make it difficult, if not impossible, to certify that the technology and its implementation are safe.

DNV GL does not have any opinion on which direction the technological development should take in terms of degrees of autonomy or remote control and the involvement of people. Instead, we aim to support the industry with robust classification services which convey trust in those solutions that are eventually certified by us.

In this paper, we refer to our role as a classification society in terms of safety assurance.

2 INTRODUCTION

Throughout history, ships have been operated by people. The number of people required for operating a ship has depended on the size, type and mission of the ship as well as the technologies utilized to carry out the various functions required to safely operate the ship for its intended purpose. Some of these functions, such as navigation and manoeuvring, mooring and anchoring, have traditionally required the attendance of one or several people for carrying out the functions and for maintaining their reliability. Other functions such as watertight integrity and stability do not typically require the attendance of people. Throughout history, technological developments have reduced the requirements for attending crew members to carry out functions. For example, the operation and maintenance of an early 20th century coal-fired steam engine for a large ship could require a crew of several hundred1), but with the introduction of diesel engines, this number decreased significantly. Increased automation of diesel engine operation and reduced requirements for maintenance have reduced the size of the machinery crew to less than ten, even for the largest engines. Recent developments in automation are, in theory, making it possible to further reduce or even eliminate the crew in attendance for carrying out ship functions. However, this requires that observations and decisions are made by crew off the ship (remote monitoring and control) or by the system itself by means of algorithms (autonomy). Reducing or eliminating the attending crew also requires that provisions be made for ensuring the reliability of these functions. If all required ship functions are fully automated and operated remotely or autonomously, one could theoretically remove all crew from the ship. However, the motivation for introducing remote-controlled and autonomous functions is not necessarily to remove attending crew, but rather to improve the efficiency of the ship's operation as well as the performance and/or safety of the function with crew in attendance. In the first part of this paper, we discuss the feasibility and merits for automating ship functions and controlling them remotely or autonomously. We also discuss the technologies required to do this and their maturity.

The main challenge for implementing fully automated systems controlled by remote operators or by algorithms is not to make them work, but to make them sufficiently safe. What is sufficiently safe, or has a tolerable risk level, will most likely be defined by a competent authority such as the International Maritime Organization (IMO) and flag states for any given operation. The competent authority would then have to build a safety regime with supporting regulations and instruments to reach this goal; a

safety regime that is also socially acceptable by the wider public. The IMO as well as some flag states have already started to evaluate what is required through the use of scoping exercises and preliminary national regulations. The second part of this paper describes the current regulatory work and suggests how a safety regime could be defined.

The safety of a ship and its operation depends on the capability and reliability of the materials and technology comprising the ship, and the skills and performance of operators of these technologies. Additionally, other external factors such as weather, traffic and infrastructure supporting the safe operation of the ships, for instance traffic control centres and ports, play an important role. Introducing novel technologies for the automation and control of these functions will potentially transform the entire system and introduce new technology risks, new societal challenges as well as new types of operations requiring new expertise. The new safety regime must therefore be able to handle these new risks. A changed risk space also leads to a changed space for assurance. The third part of this paper discusses the requirements of a safety regime in general and, particularly, the requirements for safety assurance of products and procedures enabling remotely controlled or autonomous functions.

End customers or charterers will be the ones deciding the uptake of the technology. In short: if the technology provides a solution that is more cost effective and equally reliable, safe and sustainable compared to current solutions, there will be a demand in the market for these technologies possibly outcompeting traditional ships. The business case will depend on many factors which may currently not be quantifiable and be different depending on ship type, size and operation. These factors are discussed qualitatively in the paper to offer some insights into the possible uptake of the technology. In April 2018, the IMO's Marine Environment Protection Committee (MEPC) adopted an initial strategy for reducing the total annual greenhouse gas (GHG) emissions from shipping by at least 50% by 2050. The possible impact of these new technologies on GHG emissions as well as other emissions are therefore also discussed, as this may influence the adoption and scaling of the technology due to potential regulations or market-based mechanisms introducing a cost on emissions.

Finally, the paper discusses other societal aspects and ethical considerations, effects on labour and the possible exploitation of the ocean space, as the public perception of this technological development will have a bearing on its adoption.

3 CHANGING THE WAY A SHIP IS OPERATED

A ship is operated by means of separate functions that, when combined, fulfil the objectives of the ship's operation. The performance of each function determines the performance and safety of the ship. The dynamics of the function has traditionally determined the level of involvement of a ship's crew. For the purposes of analysing the human involvement in a function, we subdivide it into four sub-tasks. These are condition detection, condition analysis, action planning, and action control (Figure 1). A static function is one that requires no or limited application of these tasks, as they do not change over time. The function of structural strength is, for example, ensured by design, and the only time it may be necessary to deploy the sub-tasks of the function is in the case that it is compromised. On the other hand, ship navigation is a highly dynamic function in which its sub-tasks must be applied continuously to ensure safe navigation.

The requirements for an attending crew to carry out a function depends on whether someone must be present to carry out or maintain the reliability of any part of the function. In this section, we analyse the main function carried out by a ship crew, namely the ship navigation, and discuss the requirements and technologies needed to eliminate the need for attending crew to reliably carry out this function. A similar analysis must be performed for any main functions to be handled remotely and/or autonomously; the example of ship navigation serves to illustrate the challenges in doing so.

3.1 NAVIGATION

For most ship types, navigation is the main function of the ship in terms of needing an attending crew. One or several crew members qualified as navigational officers must be present to carry out the condition detection, condition analysis and action planning. In addition, one or several crew members qualified to ensure the reliability of the control system and actuators must be in attendance. In this section, we discuss the possibility of introducing technology to replace the attending crew for carrying out this function.

3.1.1 Condition detection

For a ship to be navigated safely, any element that can affect the navigation must be detected in a timely manner such that it can be acted upon. These elements include geography, bathymetry, fixed objects, floating objects, weather conditions and conditions of the ship which may potentially affect its manoeuvrability. Today, such detections are carried out by a combination of a priori information, sensors and people. However, to replace the requirement for attending crew, the sensors must also replace the senses of the on-board navigators. Sensors that may be used to account for this include daylight cameras of different type (stereo, multispectral, etc.), infrared (IR) cameras and LIght Detection And Ranging (LIDAR) cameras (Figure 2), as well as sound detectors. The sensors must detect objects critical to the navigational safety of the ship and its surroundings in all feasible ambient conditions. The sensor technology may be capable of reliably doing this in fair weather conditions, but the real challenges are seen in adverse conditions such as heavy seas, darkness, fog and heavy rain or snowfall.

The position of the vessel in a navigation scenario is critical for safe operation. Currently, there is a significant reliance on GPS for this purpose. A loss of the GPS signal will therefore be critical to operations without an attending crew. Thus, the ships may need to have alternative positioning methods as a redundancy to the GPS (or independent GNSs). Robust methods for doing this based on alternative technologies for navigation should then be deployed as an alternative to GPS.

The quality of a priori information such as nautical charts will also be critical for safe navigation, as this will define the boundary conditions for the possible

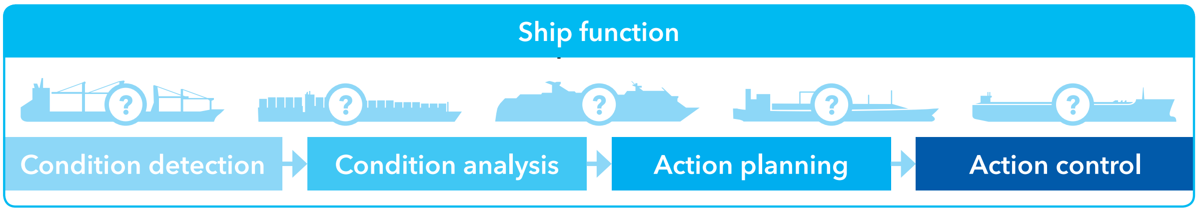

Figure 1: Generic breakdown of a ship function into sub-tasks

routes available to the ship. The accuracy of nautical charts is defined by Zones of Confidence (ZOC)[2]. These are defined in a simplified form in Table 1. The ZOC required for safe operation will typically depend on how the navigation function is carried out and the collision and grounding risk associated with the operation.

Sensors are also required to assess the capability of propulsion and steering at any given time as well as for predicting any possible changes in this capability. Sensor-based condition monitoring of all the critical components comprising the systems which ensure these capabilities will provide such an assessment.

The reliability of sensor signals must be maintained during operation. If there are no attending crew able to maintain and repair the sensors and associated acquisition systems during operations, the robustness of these systems must be proven such that maintenance and repairs can be carried out while the ship is in port. This can be ensured by means of homogeneous or heterogeneous redundancy. Homogeneous redundancy is achieved by two or more sensors measuring the same quantity; heterogeneous redundancy is when a system is instrumented with several sensors measuring different quantities, yet provides redundancy because the failure of one sensor may be remedied by calculating this quantity based on the readings from the other sensors. Heterogeneous redundancy is stronger because of a reduced dependency on the reliability of a certain sensor type.

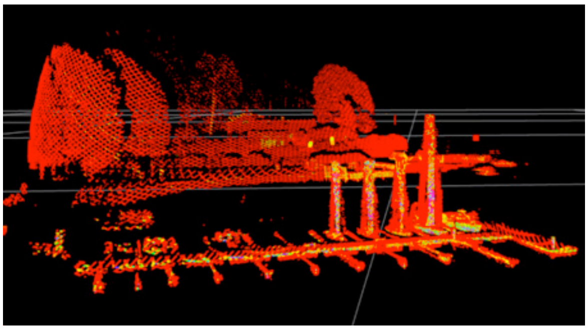

Figure 2: Rendering of a maritime environment as captured by a LIDAR

TABLE 1: ZONES OF CONFIDENCE

Zone of Confidence (ECDIS symbol)		Position accuracy	Depth accuracy
A1	✱ ✱ ✱ ✱ ✱ ✱	5 metres	0.5 metres + 1% depth
A2	✱ ✱ ✱ ✱ ✱	20 metres	1.0 metres + 2% depth
B	✱ ✱ ✱ ✱	50 metres	1.0 metres + 2% depth
C	✱ ✱ ✱	500 metres	2.0 metres + 5% depth
D	✱ ✱	More than 500 metres	More than 2.0 metres + 5% depth
U	U	Not assessed	Not assessed

Source: MySeaTime

3.1.2 Condition analysis

3.1.2.1 Autonomous

When all relevant information has been detected, this information must be collected and used to analyse the condition of the ship at any given time. Adequate situational awareness will require that all detected objects or conditions be classified and any change in state be established such that feasible future states can be determined. To eliminate the requirement for on-board crew to carry out this sub-task, it must be carried out by an algorithm or a remote crew.

For an algorithm to gain situational awareness, detected objects relevant to the navigation of the ship must be classified based on a priori information and sensor information (Figure 3). Geographical information and fixed objects can be classified from Electronic Navigational Charts (ENC). The transmission of Automatic Identification Signatures (AIS) can be used to classify other ships. However, in cases where ships do not transmit a reliable AIS signal at a sufficient frequency, or for small ships or floating objects that do not transmit AIS signals, exteroceptive sensors such as radar and cameras have to be used. Cameras can be particularly useful in this context, and the field of computer vision, where a camera is coupled with software to gain a high-level understanding of a digital picture or video, is maturing within several areas. However, in the maritime context, this technology is rather immature because computer vision is usually based on machine learning, which relies on pre-existing data and must thus be trained by a library of relevant pictures or video footage whose availability is currently limited. Other sensors, such as acoustic sensors, may also be required in situations where the visual sensors are incapable of classifying objects due to poor visibility.

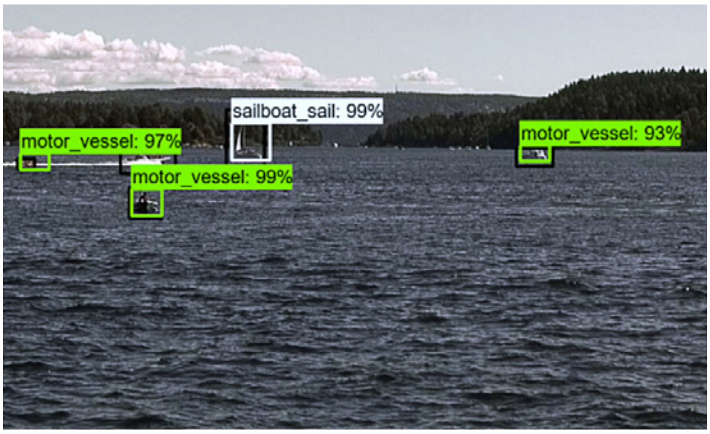

Figure 3: Classification of objects relevant to safe navigation

Figure 4: Exchange of routes between manned and unmanned ships

There are at least two main strategies for fusing object detection and categorization from multiple sensors: “detect and fuse” and “fuse and detect”. In the former, objects are detected and categorized by each individual sensor system, then these results are merged into a common situational awareness by a sensor fusion algorithm. In the latter, raw data from all the sensor systems are fed into an algorithm that directly performs detection and categorization, typically based on machine learning. The choice of strategy will affect the transparency and complexity of the solution, and consequently the possible assurance schemes.

The condition analysis algorithm will need to predict possible future states by assessing the most likely plan and/or capability of objects affecting the safe navigation of the ship. One way of achieving this for commercial ships is to require ships to electronically exchange their intended route; formats for route exchange have been defined in IEC 61174[3)]. This has also been researched and tested in projects such as the EU-funded MONALISA/STM Validation Project[4)] for route exchange between manned ships, but this philosophy can also be used to introduce a shared situational awareness between an on-board navigator and an autonomous ship or between two autonomous ships. If such a functionality is implemented, the remaining challenge for the autonomous system will be to evaluate the intention of objects that do not share this information electronically. One way is to classify the objects, and then based on their current movement and estimated capabilities, dynamically assess their likely future position – allowing for a risk-based approach to navigation, emulating that of a human navigator. The situational awareness algorithm must also be able to carry out diagnostics and prognostics based on signals from proprioceptive sensors defining the condition of the on-board equipment critical to navigation and the corresponding estimated navigational capability based on exteroceptive sensors measuring the metocean conditions. Since the autonomous situational awareness is based on an algorithm, this requires no maintenance in the classical sense. However, algorithms are often subject to upgrades due to errors that have been detected, performance improvements or their attributes. Maintenance of the hardware and network components where the system is running will also be needed.

3.1.2.2 Remote control

For a remote operator to gain adequate situational awareness, sufficient information must be transferred from the sensors on the ship to a remote control centre (Figure 5) in a timely manner. This puts requirements on the type, volume and latency of information transmitted and the way it is presented to the remote operator. The same sensors and algorithms used for the autonomous situational awareness system discussed above can be utilized, but the information needs to be presented in a way that it supports the remote operator's cognitive abilities. Additional or alternative information may also be needed to support the remote operator. The ability of an operator to correctly perceive the situation and perform proper action highly depends on the type and quality of the information presented. Research[5] suggests that an operator needs a condensed and focused view with only a few top-level indicators, but with the possibility of accessing a rich set of system status information to judge the situation correctly; not just information from the system directly operated or monitored, but also information from subsystems and components at lower system levels[6].

If one had unlimited, reliable and ubiquitous communications capacity, one could envisage replicating all the information available on an on-board bridge to a remote bridge using sensors. However, even if ship connectivity is continuously improving, the quality required for safely navigating a ship by remote control has only been put to the test in areas with significant communications capacity[7]. The peak capacity required to transmit live information from sensors that may be required for remote navigation may

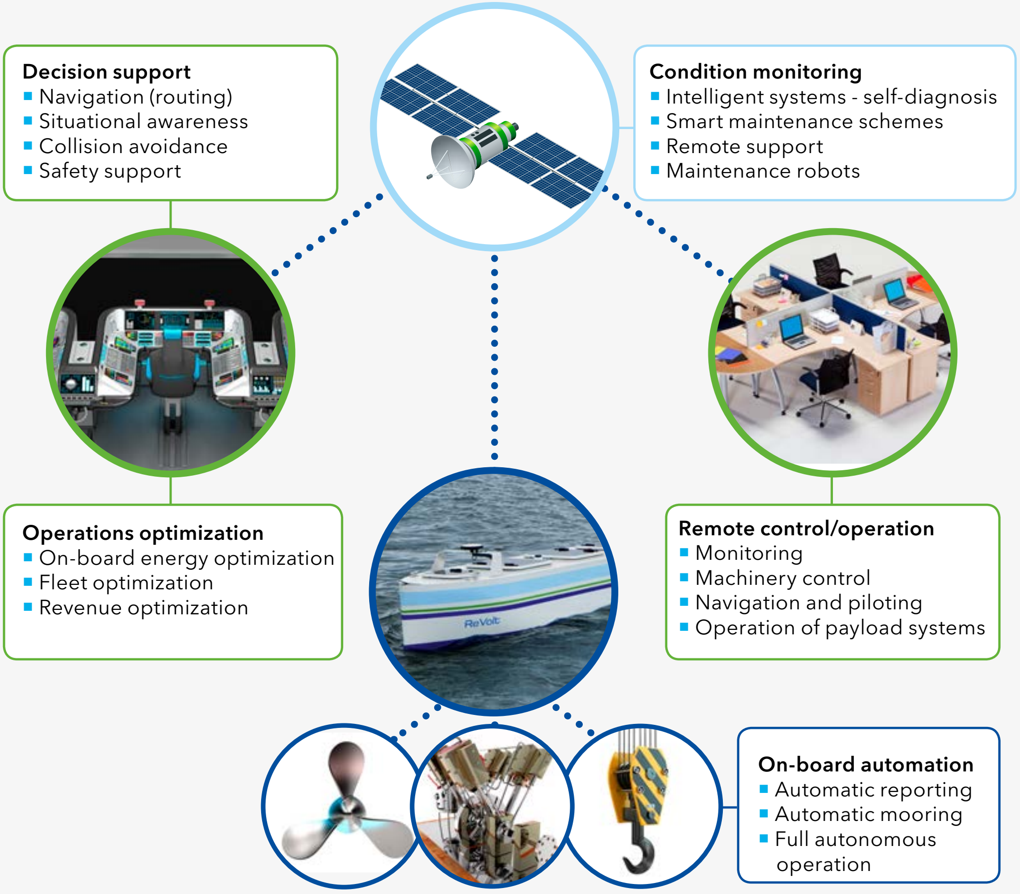

Figure 5: Picture of remote control centre

Figure 6: Ship with communications equipment

be as much as several tens of megabits per second depending on the sensors used. Although it is possible to handle such a capacity even through satellite communication, it is difficult to scale this to many ships, given the current state-of-the art communication systems. The availability, latency and capacity of communication will depend on the communication bearers available at the specific location of the ship, the communication technology available on the ship and at the remote control centre. Ships operating close to the shore will be able to take advantage of terrestrial communication bearers such as radio and mobile systems, whereas ships operating on the high seas must rely on satellite communication. These systems have very different properties when it comes to critical parameters like availability, latency and capacity. The availability of the required quality of communications is of such importance that there needs to be sufficient redundancy in equipment to ensure this. It is possible to reduce the required capacity for transmission of information by reducing the raw data transmitted with respect to parameters such as field of view, resolution, colour depth and frame rate. Preprocessing of the information before transmission by methods such as background subtraction can also be used to reduce the amount of information to be transmitted. Post-processing of the information as well as augmentation to aid the situational awareness of the operator will likely take place at the location of the operator or by means of cloud-based solutions.

The reliability of the situational awareness in a remote control centre must be ensured by proper maintenance of the on-board and remote communications equipment as well as the equipment in the remote control centre. Since maintenance of the communications equipment on board may not be carried out during ship operation, the reliability should be such that maintenance is carried out while the ship is in port.

3.1.3 Action planning

Once the condition has been analysed and sufficient situational awareness achieved, the course of action must be planned based on this analysis as well as a predefined ship mission and a set of predescribed rules such as the International Regulations for Preventing Collisions at Sea (COLREGs)[8].

3.1.3.1 Autonomous

For a navigation system to be autonomous, the planning must be carried out by an algorithm rather than a human operator. Decision-making algorithms can be preprogrammed or self-learning. In a preprogrammed navigation algorithm, the decisions are programmed into the software based on the COLREGs. However, the COLREGs do not cover every possible navigational situation. A set of rules must therefore also be defined to handle these situations. Alternatively, the algorithm can be self-learning based on Artificial Intelligence (AI) technology. The self-learning algorithm would still have to conform to the COLREGs, but the situations which lie outside the COLREGs do not need to be prescribed by a set of rules. Rather, the algorithm is trained by the process of machine learning. The training of the algorithms can be carried out from data generated by a simulated environment, by field testing and by operational data. Most likely it will be a combination of these, however using a simulated environment will probably be necessary in order to obtain the sufficient amount and diversity of training data – for example the algorithms need to be trained by adverse situations not frequently seen in real operation. The algorithm will also be able to become frequently updated through new training data that is continuously collected during actual operation, possibly from many ships in parallel. Once the algorithm has been updated, it can be retested and deployed. It is possible that future algorithms might learn during operation, i.e. while deployed, and then be able to exhibit changed behaviour, but this capability is not foreseen in the immediate future. Indeed, there might be strict requirements related to this to avoid unintended behaviour. The quality of both preprogrammed and self-learning algorithms will improve with increasing knowledge of possible navigational scenarios.

A significant challenge related to COLREG-compliant algorithms for navigation is that the COLREGs are written for a human operator, and sometimes the requirements are qualitative and open to interpretation. If the COLREGs are to be embedded in an algorithm for making navigational decisions, there can be no room for interpretation, because two algorithms interpreting the regulations differently may cause an accident. Efforts should therefore be made to make quantitative COLREGs with clearly defined rules to avoid different interpretations. Such COLREGs can be developed and maintained by the industry. This approach has been adopted in the aviation industry, where a quantitative rule set for anti-collision has been developed by the industry and deployed in anti-collision algorithms (TCAS) for planes. The development of anti-collision systems for planes started due to several serious mid-air collisions, and today these systems take precedence to the pilot or the air traffic controllers. This is important because it makes sure that the quantitative rules are followed by all planes. The Überlingen accident[9)] (see box) illustrates the possible consequence of not adhering to this requirement.

On the night of 1 July 2002, the Bashkirian Airlines flight 2937, a Tupolev Tu-154 passenger jet, and the DHL flight 611, a Boeing 757 cargo jet, collided in mid-air over Überlingen, a southern German town on Lake Constance. All 69 passengers and crew aboard the Tupolev and the two crew members of the Boeing were killed.

The official investigation by the German Federal Bureau of Aircraft Accident Investigation identified as the main cause of the collision a number of shortcomings on the part of the Swiss air traffic control service in charge of the sector involved, and also ambiguities in the procedures regarding the use of TCAS, the on-board aircraft collision avoidance system. (Source: Wikipedia)

3.1.3.2 Remote control

For remote-controlled navigation of a ship, the planning and decisions will ultimately be carried out by a remote navigator. The remote navigator can make direct decisions based on the situational awareness presented, or evaluate decisions made by an algorithm as described above, in a decision support or navigator assistance context. However, in the end the final decision will be a result of the best judgement of a human operator, putting stringent requirements on how the condition analysis is presented to the operator and the performance of the operator in the relevant context. It should be noted that the competence and required skills of a remote navigator may not be the same as those of a traditional navigational officer. In the context of a purely remote-controlled ship, the existing COLREGs may be adopted, but an increasing degree of autonomous action planning will require an increasing degree of quantitative requirements as part of the COLREGs. There are additional challenges for using the existing COLREGs for a purely remote-controlled ship, because the COLREGs do not explicitly state at what distance a manoeuvre should be initiated. The range requirements for the sensor systems are therefore not clearly defined.

Figure 7: Plane traffic

3.1.4 Action control

When the action has been planned and a decision has been made, this decision must be actuated. Navigational decisions are actuated by the components providing thrust and steering capabilities such as propulsion systems and rudders (Figure 8). Control systems also ensure that the resulting manoeuvre is in accordance with the input. For an autonomous system, the control commands will be generated and sent from the action planning software to the control system. The reliability of the action control will depend on the reliability of the control system and the actuators. This reliability may be ensured by means of maintenance. If there are no crew in attendance to carry out this maintenance, a different strategy must be deployed where maintenance is carried out when the ship is in port. Such a strategy may compromise the reliability of the control system and actuators, but this may be compensated for by introducing redundancy of components and systems. The requirements for redundancy will depend on the risk associated with the failure of the component or system. One measure that may be introduced to increase reliability and reduce the need for redundancies is alternative maintenance practice based on condition monitoring as has been illustrated in the aviation industry (see box)[10]. A current challenge with condition monitoring, and associated diagnostics and prognostics of ship components and systems, is the lack of standardization of these systems. As diagnostics and prognostics are commonly data-driven, a large data set is needed for reliability. In the aviation industry, such large data sets are available due to large-scale implementation of standardized components and solutions, whereas in the shipping industry customization of equipment is more common. Successful implementation of condition-based maintenance principles may therefore depend on increased standardization of equipment and increased use of integrated modules.

In 1953, the USA developed regulations that prohibited two-engine planes from routes more than 60 minutes (single-engine flying time) from an adequate airport. The Extended-range Twin-engine Operations (ETOPS) programme, as outlined in FAA Advisory Circular (AC) 120-42A, allows operators to deviate from this rule under certain conditions. By incorporating specific hardware improvements and establishing specific maintenance and operational procedures, operators can fly extended distances up to 180 minutes from the alternate airport. The ETOPS maintenance approach that can be applied to all commercial planes includes:

1. Engine health monitoring
2. Predeparture service check
3. Basic and multiple-system maintenance practices
4. Event-oriented reliability programme (Source: Boeing)

For a remotely controlled system, the control command is provided by the remote operator. In this case, the reliability of the action control will also depend on the reliability of the communications between the remote control centre and the ship. The capacity requirements will be reduced when compared to condition analysis, but the reliability and latency of the communications link is equally important, and requirements to redundancy and maintenance of the communications equipment is therefore equally important for remote action control.

Figure 8: Actuators of ship navigation

3.1.5 Likely technology implementation

In the above sections, it was described how it may be possible to replace attending crew by automation controlled by autonomous or remote-controlled solutions. However, in a real-life deployment of this technology the solution will probably not rely on either autonomy or remote control, but a combination of the two. The main reason for this being that it will improve the reliability and the performance of the solution. Remote control is particularly vulnerable to downtime in the communication link, and a loss of connectivity will not be acceptable because it will render the ship out of control. However, if the ship has an autonomous navigation system in addition, this would (presumably) be able to reliably control the ship while the communication link is down. Conversely, if the ship is completely reliant on an autonomous navigation system, the reliability will be dependent on the ability of the algorithms for condition analysis and action planning to make the right decisions for all scenarios and in all conditions. This can be remedied by a remote operator able to verify or adjust these decisions. The reliability of the algorithms will also depend on the amount of data available for verifying or training the algorithms. For this purpose, a remote operator can contribute to a controlled training and verification of the algorithms, meaning that these will improve with time. As the reliability of the algorithms increases, the required involvement of the remote operator will decrease, but it is questionable at what point or whether it is at all feasible to eliminate the need for a remote operator. This will depend on the complexity and criticality of the function or sub-tasks.

Another likely implementation of an autonomous navigation system is as a solution providing decision support or navigational assistance for a ship with a

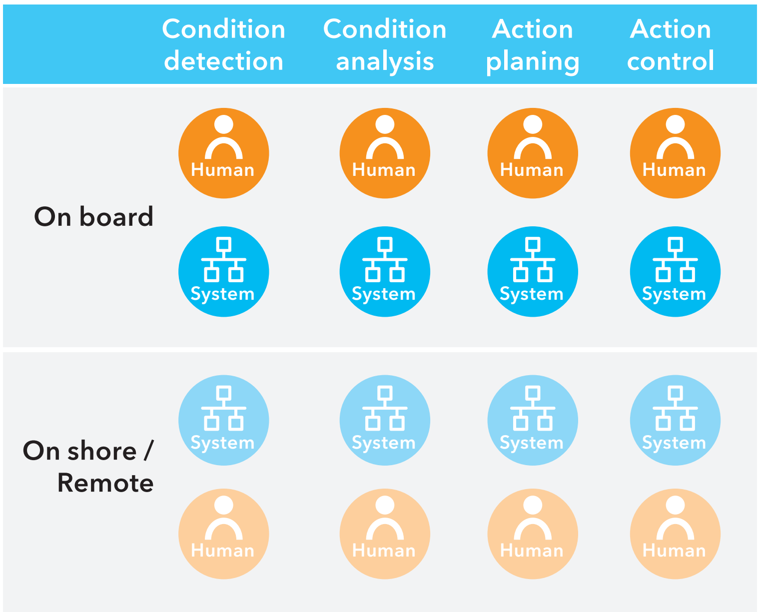

Figure 9: Functional breakdown with assigned responsibility and location

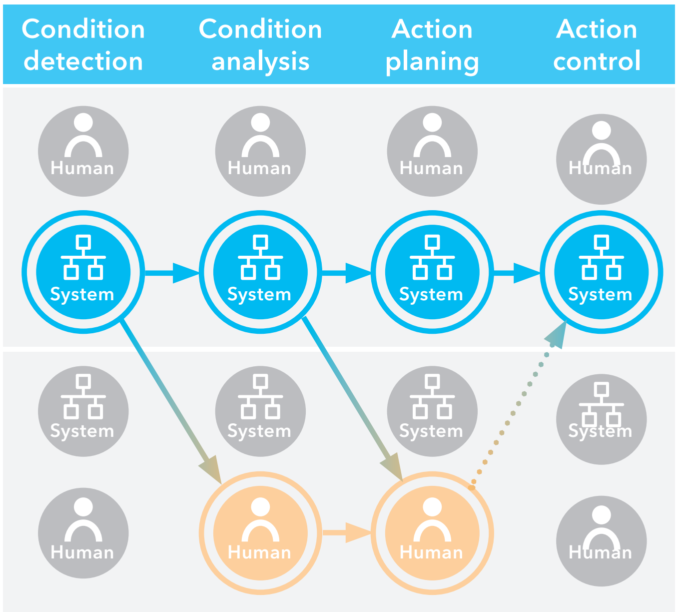

Figure 10: Example of a functional definition

crew in attendance. Such systems have increasingly been implemented for many transport solutions such as already mentioned, for planes in terms of automated anti-collision systems (TCAS) and for cars in terms of adaptive cruise control and even anti-collision systems in some parts of the world.

In Figure 9, the subdivision of a ship function, as detailed in Figure 1, is shown in the context of assigning responsibility to the sub-task as well as the location where the sub-task is performed. From the figure it is evident that there are many possibilities of combining solutions for how to carry out a function. Figure 10 illustrates a remotely supervised on-board autonomous system, with the option of remote control. For every function, it should be possible to map out a similar diagram showing the intended functionality of the system. The division of responsibility will determine the level of autonomy or remote control. The default control in Figure 10 is indicated by a solid line, whereas the dotted line illustrates the override option, showing that by default the navigation is carried out by the on-board autonomous system, whereas the remote operator has the possibility to override the decisions of the autonomous system, thereby giving the operator priority in terms of responsibility. This offers an alternative way of defining how a function is carried out, including the level of human involvement, the level of autonomy and remote control, the default functionality and the back-up solution as well as the assignment of responsibility. Many of the existing attempts at categorizing levels of autonomy for ships[11,12,13] fails to capture one or more of these elements.

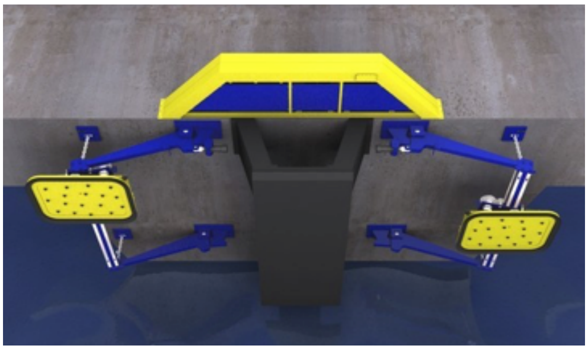

Figure 11: Automatic mooring system eliminating requirements for mooring from ship side

3.2 OTHER SHIP FUNCTIONS

Some ship functions such as watertight integrity, stability, mooring and anchoring are common to most ships, whereas other ship functions are completely dependent on the mission profile of the ship, such as cargo handling for a cargo ship or servicing of passengers for cruise ships. For any function to be carried out without the need for an attending crew, considerations on how to detect, analyse, plan and control must be carried out. For a ship to be completely unmanned, all required ship functions must be carried out remotely or autonomously. Alternatively, the need for the function must be eliminated (Figure 11) or carried out when the ship is in port or in dock.

4 REGULATION

4.1 STATUS OF INTERNATIONAL REGULATORY DEVELOPMENTS

The societal expectations to any technological development is that it is implemented without adversely affecting the safety of people and property and that it does not negatively impact other aspects of society or the environment. The evaluation of whether the technology implementation is negative or positive may depend on your point of view. At the international level, regulation relating to safety, security and environmental protection is mainly the responsibility of the United Nations' (UN's) International Maritime Organization (IMO). National or regional regulatory bodies are, however, to some degree free to issue additional or supporting regulations within their jurisdiction or territorial waters.

Autonomous ships were put on the international regulatory agenda by Denmark et al. (2017)[14). The proposed task for the IMO was to carry out a regulatory scoping exercise with the aim of identifying:

1. IMO regulations which, as currently drafted, preclude unmanned operations;
2. IMO regulations that would have no application to unmanned operations (as they relate purely to a human presence on board); and
3. IMO regulations which do not preclude unmanned operations but may need to be amended in order to ensure that the construction and operation of Maritime Autonomous Surface Ships (MASS) are carried out safely, securely and in an environmentally sound manner.

Four sessions of the Maritime Safety Committee (MSC) were proposed to be used for this scoping, with the aim to finalize the study by May/June 2020. No work on amending any regulations is yet planned.

In 2017, the International Transport Workers' Federation (ITF) submitted a commenting paper[15). Amongst other proposed actions, the ITF proposed to consider implications of IMO treaty regimes and the United Nations Convention on the Law of the Sea (UNCLOS) for unmanned ships. There was general support for both proposals. If the scoping exercise concludes that the UNCLOS needs to be amended, this is outside the IMO's jurisdiction and will most likely prolong the process. The United Nations Division for Ocean Affairs and the Law of the Sea will then need to be consulted to decide on the way forward. The relation between the United Nations Division for Ocean Affairs and the IMO will be handled by the IMO Legal Committee, which also has agreed to carry out a scoping study. Currently, there is no proposal on how the required amendments should be identified, drafted, agreed and implemented. Many flag states and non-governmental organizations (NGOs) are now contributing to the scoping study and have identified a long list of required amendments to regulatory instruments.

There are few impediments for reducing manning further than today, provided the systems on board were more self-governing and in need for less inspection, maintenance and repair. The current safe

manning regulation even states this explicitly. The IMO (2011) regulations on safe manning[16)] demonstrate that the IMO Assembly has thought of the effect of more automation and support from ashore in deciding on safe manning, although the purpose was not to prepare for unmanned ships:

“The minimum safe manning of a ship should be established taking into account all relevant factors, including the level of ship automation and the degree of shore-side support provided to the ship by the company. The Administration may require the company responsible for the operation of the ship to prepare and submit its proposal for the minimum safe manning of a ship in accordance with a form specified by the Administration.”

It is worth noting that on this subject, the flag state may expect to be audited according to the IMO Instruments Implementation Code (IMO, 2013)[17)].

The most explicit impediments for reduced manning can be found in STCW CHAPTER VIII, Watchkeeping, Regulation VIII/2, Watchkeeping arrangements and principles to be observed. Regulation VIII/2 uses the term “physically present” on board:

- Administrations shall require the master of every ship to ensure that watchkeeping arrangements are adequate for maintaining a safe watch or watches, taking into account the prevailing circumstances and conditions and that, under the master’s general direction,:
    - officers in charge of the navigational watch are responsible for navigating the ship safely during their periods of duty, when they shall be physically present on the navigating bridge or in a directly associated location such as the chartroom or bridge control room at all times; and
    - officers in charge of an engineering watch, as defined in the STCW Code, under the direction of the chief engineer officer, shall be immediately available and on call to attend the machinery spaces and, when required, shall be physically present in the machinery space during their periods of responsibility.

The first paragraph would need to be amended to reduce the manning below current minimum levels, whilst the second paragraph allows the reduction to one chief engineer, in case there is sufficient automation and shore-side support, for example from a remote control centre. In the STCW case, there is a rather specific description in STCW/I/13 of how to get around these requirements by organizing trials. Several of the studies submitted mention these and other challenges. In general, all international regulations are developed under the assumption that there are trained and certified crew on board the ship. For example, a search for the term “alarm” in IMO Vega (database for IMO and some other international regulations) finds 889 documents containing the term. All these references to alarms would need to specify different requirement in at least two versions: one for fully autonomous operation and one for remote-controlled operation. Similarly, a search for “alarm” in IACS UR M (Machinery) shows that the term is used about 180 times. Other URs and individual class rules will indicate further challenges and needs for alternative rules and regulations for autonomous and remote-controlled ship functions. In their scoping study, Finland et al. (2018)[18)] identifies that amendments may be required in more than 30 codes and conventions.

All projects and activities on autonomous or remote-controlled ships so far are either 1) under national regulations or 2) exempted from international regulations (small or navy vessels). Many of the ongoing projects are also exempted from national regulations. Several national administrations are authorized to grant such exemptions (mainly for trials and R&D activities). Other nations have large parts of the maritime regulation as national laws, and the national administration has not been delegated authority to grant such exemptions. This varies between states, and can be understood by considering national regulatory traditions and state governance structures. Most national laws contain definitions of who to arrest in case of fault. For an autonomous or remote-controlled ship, at least, this part of the regulations needs to be changed in most national laws. This will not necessarily be straightforward, but work has already been started to evaluate how to handle the issue of liability.[19)]

4.2 THE WAY FORWARD

The scoping studies carried out by the MSC tend to focus on regulations that need to be amended. This is a direct result of the proposal for the scoping study by Denmark et al. (2017)14). However, some have started to look for alternative solutions. The IMO Secretariat (2018)20) suggests four alternatives for a regulatory framework:

1. Amending existing instruments, taking into account the different amendment procedures for specific instruments or regulations and the time and means required to bring the necessary amendments into force
2. Developing a new separate instrument addressing MASS
3. A combination of options 1 and 2 above
4. The development of interim guidelines to gain experience before commencing work on mandatory requirements

The amendment of all conventions is going to be an extremely time-consuming task, and this may not be a practical approach. It will have to involve all IMO committees and subcommittees and most conventions and codes.

A separate instrument could be in the form of a convention or a code. A new convention would only apply to autonomous and remote-controlled ships. However, no ship would be only autonomous or remotely controlled; it would be a ship type, with a specific operation in addition to being autonomous and/or remotely controlled. Multiple conventions and/or codes would apply to a ship. The requirements would also in this case need to be formulated in at least two versions: fully autonomous or fully remotely controlled, and in various combinations of autonomous and remote control. This could only be avoided if the new convention was goal-based, and the functional requirements formulated sufficiently generic to be applicable for both cases (and all cases in between). The challenge of ratification would remain. It would take time, and it would be very uncertain how long it would take until a new convention was ratified.

A new code would be a simpler and more practical option, even though many of the same challenges for a new convention would be relevant for a new code. However, if the code was made mandatory under SOLAS (with a new SOLAS chapter as an anchoring point), the use of the code would have the same application as a convention. If the code was mandated by a two-thirds majority, ratification challenges would be avoided. Even if it is decided to develop a new convention or code, amendments of other regulatory instruments must take place where these contain explicit showstoppers.

An interim solution may be linked to STCW/I/13 in which there is already a reference to a non-existent guideline. Paragraph 3 of STCW/I/13 states, "The Administration authorizing ships to participate in trials shall be satisfied that such trials are conducted in a manner that provides at least the same degree of safety, security and pollution prevention as provided by these regulations. Such trials shall be conducted in accordance with guidelines adopted by the Organization." Since such guidelines do not exist, the first task could be to develop them. The chances of progress would also be better if the initial scope was limited by excluding ships and operations that are unlikely to be carried out autonomously or by remote control. For example, China and Liberia (2018)21) propose to focus on "unmanned cargo carriers". However, the term "cargo carrier" would then have to be defined. Currently, this is not a defined ship type in IMO instruments.

The DNV GL recommendation is to first develop an interim guideline and, ultimately, to develop a new Autonomous Ship Code (ASC), anchored and mandated in SOLAS. The adoption of an ASC would need to be followed by a process of consequential amendments of many conventions and codes. This could largely be done by referring to the ASC. It is expected that the enabling technologies applicable to remote-controlled and autonomous ships will be developing fast. New and better technology will enter the market frequently, making it impractical to formulate detailed technical requirements (algorithms, sensors, data fusion, etc.) at the IMO level. It is therefore suggested that the code should be goal-based. The aim of the goal-based code should be: "Autonomous and remote-controlled ships shall be as safe as conventional ships of the same type", or a similar formulation. It should then be left to the class societies to develop specific rules that define an assurance procedure complying with the code. The classification societies would then have to justify their rules, documenting that the rules meet the goals and functional requirements of the code. Figure 12 shows a suggested structure of the new ASC and the supporting documents.

The industry will also apply their own requirements and standards, be it industry-wide or company specific. This is illustrated as Tier V in the figure. These could be applied in addition to the minimum requirements to create competitive advantage to a solution or increased safety for a stakeholder wishing to protect their asset.

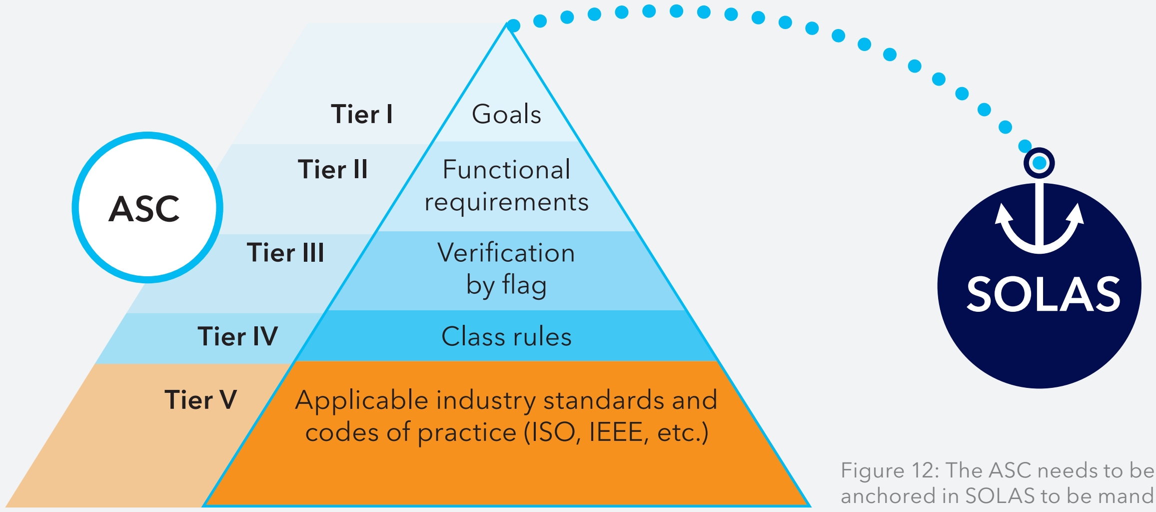

Figure 12: The ASC needs to be anchored in SOLAS to be mandated.

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5 SAFETY AND SAFETY ASSURANCE

The current safety regime is designed to ensure implementation of the current regulatory regime, giving safety assurance to traditional ships with human operators, where the main risks are related to human errors and failure of components and systems. These will still be failure modes that need to be addressed in the context of remote-controlled or autonomous ship functions, but in this context, some of the main risk factors are likely related to sensors, software and communications. These are already risk factors that are becoming increasingly relevant for traditional ships, but the current safety regime is not adequately handling these risks, mainly relying on human fallback and a partly false dependence on redundancy. For autonomous and remote-controlled ships, this deficiency in the safety regime will become even more evident, and likely unacceptable from a risk perspective. In addition, the vulnerabilities of software-based systems to cyber threats also represent an increased risk. The question is then: How should the safety regime be designed to ensure safety assurance for such systems?

5.1 SHIP SAFETY

The safety of a ship is a complex issue related to several parameters associated with risk. These parameters include:

- The well-being of the ship crew and passengers
- The value of the ship and assets on the ship
- The well-being of people external to the ship
- The value of assets external to the ship
- The impact on the environment

Risk is a function of the probability and the consequence of an event. The effect of reducing or eliminating crew in attendance by the introduction of sensors, algorithms and remote control centres on the probability of a safety-related event occurring will be determined by the performance of the technology or remote operator, compared to that of the crew for carrying out the same function. Advocates of autonomy claim that crew are responsible for as much as 80% of ship-related accidents[22]. Thus, it is often claimed that replacing this crew with robust technologies for automation and autonomy will have the potential of dramatically increasing the safety of ships. However, it can also be argued that a ship accident is an anomaly, and that the attending crew are an essential factor to ensuring the effective and successful operations of ships and handling of safety and security issues. In this context, it is very possible that the best effect on safety can be achieved by introducing automation and autonomous technologies for decision support or operator assistance systems for a ship with a crew in attendance or by remote operations. For a remote-controlled function, human error will still be a contributing factor for the occurrence of accidents, but also a mitigating factor for avoiding them.

The removal of an attending crew will influence the consequence of an accident. Removing or eliminating the crew will naturally reduce any consequences related to the well-being of this crew, but the effects on values on and off the ship as well as the environment and humans off the ship will depend on the ability of the automation and autonomous technologies and/or a remote operator to mitigate the effects of an accident as compared to that of an attending crew. The effect of reducing or eliminating a ship crew on risk is therefore not evident, but the main factor influencing this will be the performance and robustness of the technology and/or remote operators intended to replace the attending crew. Clearly, the technologies that enable remote-controlled or autonomous ships change traditional safety considerations, introducing new risks and lessening others. Any alternative solution will be mandated to be at least as safe as the current state of the art, but the ultimate goal should be to dramatically improve safety. DNV GL does not have an opinion on which solution will have the lowest risk; but for any solution developed, DNV GL aims to have a robust and reliable safety assurance regime in place which facilitates safe implementation.

5.2 SAFETY ASSURANCE

The term assurance is defined as being "ground for justified confidence", and the level of required confidence depends on a system's criticality. Confidence is established by providing evidence that the system meets defined requirements, and this evidence should be complete, correct, relevant and objective. Thus, verification is defined as "the process of providing objective evidence". A company like DNV GL evaluates evidence through, for instance, review, analysis and testing. The required confidence level will determine the level of rigor in the verification effort to assess conformity to the set requirements.

In the rest of this section, the requirements and verification procedures needed to provide assurance are related to the ship navigation function example as described above, where the function was broken down into the four sub-tasks of condition detection, condition analysis, action planning and action control (Figure 1).

5.2.1 Condition detection

Requirements must be put on the detectability of all objects or conditions relevant for safe navigation and the quality of this detection. With respect to a priori information such as ENC, these can be verified by the applicable ZOC for the area of operation. Sensors will be responsible for the majority of detection required for both autonomous and remote-controlled systems. Requirements must be defined for the detectability and robustness of individual sensors or sensor systems as based on the chosen sensor fusion strategy. These requirements will depend on the actual operation of the ship related to parameters such as speed and manoeuvrability. Verification procedures must then be defined to verify that the detectability is in accordance with the requirements. This will likely require field testing of individual sensors, sensor systems or both. It is infeasible to test detectability in all possible operating and ambient conditions, so the testing should be designed to provide the highest possible assurance at minimum cost. The reliability of the sensor system must also be ensured throughout the lifetime of the ship by means of sensor system design approvals as well as by remote or on-premise testing and periodic inspections. Sensor failures represent a significant threat to the safety of the system. The availability of these systems can also be increased by introducing redundancy requirements and/or diagnostics for the most safety-critical sensors.

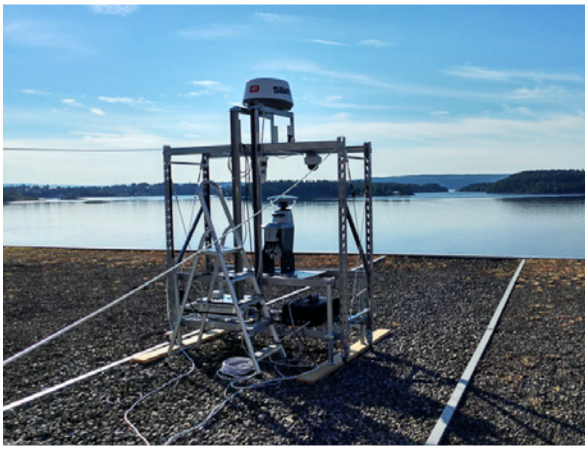

Figure 13: DNV GL test rig for testing the performance of sensors for condition detection

5.2.2 Condition analysis and action planning

The assurance of the condition analysis and action planning is considered in combination because the reliability of both sub-tasks is closely linked. Both will be carried out by an algorithm for an autonomous system and by a remote operator for a remote-controlled system.

For autonomous navigation, the condition analysis and action planning will be based on algorithms. For the algorithms to be evaluated as safe, the verification needs to demonstrate that it will conform to the relevant requirements such as COLREGs. Such assurance is difficult to provide by means of field testing only, because it is infeasible to test the algorithm in a sufficient number of situations in order to provide adequate proof. The automotive industry has mainly been pursuing assurance by following the field testing strategy, but as is claimed in literature[23] and shown by recent accidents where autonomous cars have been involved[24],[25], this strategy may not provide adequate safety assurance. For ships, it is even less likely that field testing will provide sufficient assurance, because relevant critical situations occur less frequently for ships than for cars. An alternative to field testing is to create a simulated environment where sensor signals, based on the relevant physical testing of sensors as well as other a priori information, are simulated and used to generate a number of virtual test scenarios which the condition analysis and action planning algorithm can be tested against. This will give increased assurance because it makes it possible to generate the most challenging scenarios imaginable. The algorithms can then be evaluated against a large set of scenarios, since it will be possible to run the scenarios in an automated way and most probably faster than real time. Another advantage with simulator-based verification is that it makes it possible to verify the functionality implemented in software independently of the physical parts such as sensors, thus enabling parallelism and improving efficiency in the verification process. For assurance of the algorithm, this approach is likely the one that will provide the highest level of confidence, but it should be complemented by dedicated testing during sea trials for purposes of validation. Continuous assessment of the performance of the algorithm during

Figure 14: Digital twin of ship

operation to quickly detect and correct any anomaly may also be required. This can be done by means of on-site or remote observations or built-in assurance algorithms dedicated to evaluating the performance of the operational algorithm. In order to perform simulator-based verification, a digital twin of the real vessel is needed (Figure 14).

A digital twin is a digital representation of a specific physical asset, process or system. In the context of simulator-based testing, a digital twin is a comprehensive mathematical model of the physical asset and its equipment, including all sensors and actuators, actual control system software and emulated control system hardware. As an example, a digital twin of a real vessel (Figure 15) will include mathematical models of the physical ship, including the ship-specific vessel dynamics, power system, propulsion system, positioning system, ballast system and sensor systems, in addition to the control systems such as dynamic positioning, automation systems, and autonomous and remote navigation systems. The digital twin will normally be considered as a black box system, meaning that only equipment and system manufacturers have detailed insight into their models and software systems. The digital twin resides in an operating environment consisting of the metocean conditions, its geographic location, including land masses, and other traffic, including dynamic interaction effects with the digital twin. The operating environment should be a white or grey box system, meaning that at least some level of insight into its workings must be available to a verification organization. In the simulator-based verification process, the digital twin and its operating environment are controlled by at test management system through a dedicated test interface. The test management system consists of two main functions: a scenario manager that sets up and schedules simulation scenarios, and a test evaluation system containing safety assessments, digital rules and regulations. The test management system must be a white box system for the verification organization, meaning that it gives full insight in and control of both scenario management and test evaluation.

Simulator-based verification can focus on performing operational scenarios (function testing), failure scenarios (failure and failure tolerance, reliability and degraded function) and performance testing. For condition analysis and action planning, running a large set of operational scenarios poses the main challenge, whereas for action control and condition detection, failure tolerance and reliability are more relevant.

Simulator-based verification should be followed by full-scale testing to validate the correctness of the digital twin. This can be done by performing the physical verification scope on the simulator-based tool and comparing the results, or by performing specific physical tests to validate certain critical digital models in the digital twin. With these results, confidence in the simulator-based verification can be achieved.

The use of AI, including machine learning techniques for optimizing the algorithms, will provide an additional layer of complexity to the verification process. Machine learning technology can be deployed for

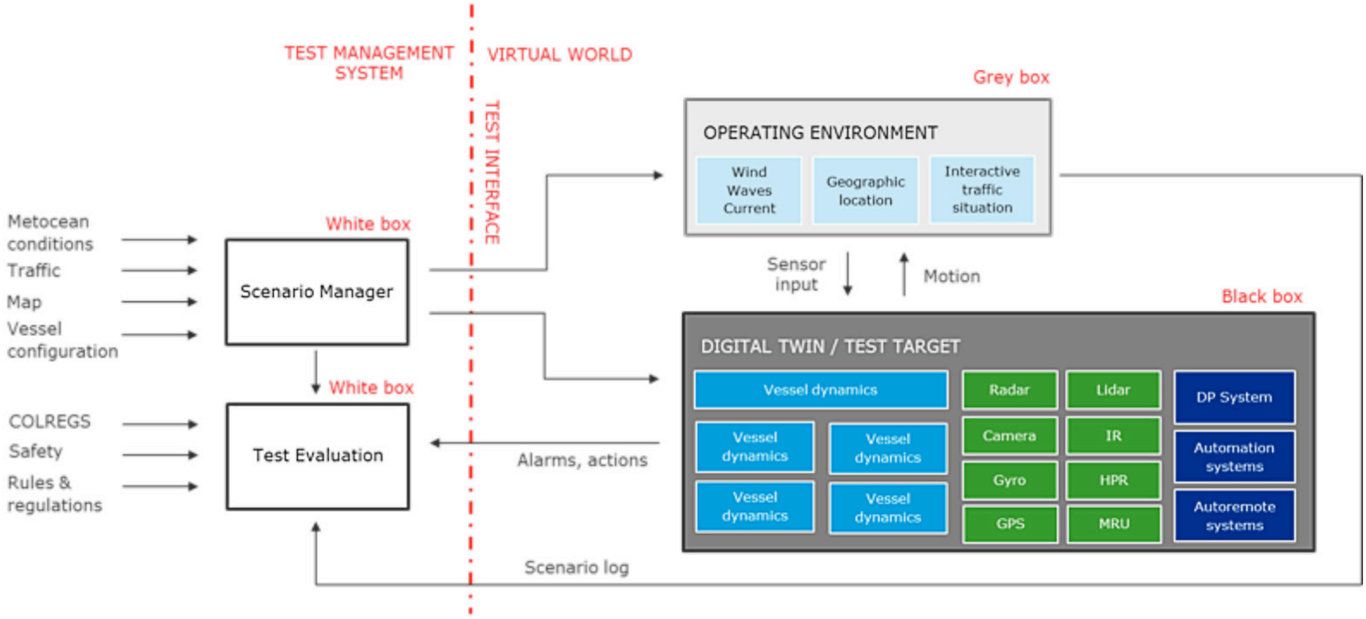

Figure 15: Digital twin, operating environment and test management system

improving different parts of the algorithm, such as the object classification, by means of computer vision or for improving the performance of the ship by route optimization. The use of this technology may be prohibited for safety-critical elements in the algorithm, as is currently recommended by IEC 61508 for safety levels beyond Safety Integrity Level 1 (SIL1). Alternatively, the verification requirements may be stringent and carried out at discrete and controlled intervals, only allowing for updates to the algorithm in use once this has been verified, or requiring algorithms that are transparent by design. However, restricting the implementation of AI and machine learning may also decrease the quality of the algorithms. These methods have, for example, been proven to accelerate the performance of autonomous cars. DNV GL is therefore involved in research related to the assurance of AI algorithms so that, in time, these can be safely implemented.

For remote-controlled navigation, the condition analysis and action planning will be carried out by a remote operator. The remote operator must be able to make sense of the information provided in time to make the right decisions. This puts requirements on the connectivity between the ship and the remote control centre, on the way in which information is presented to the remote operator and on the qualifications of the remote operator.

The connectivity requirements will depend on the criticality and type of ongoing ship operation as well as the effect of the reliability of communications on the risk of the operation. For example, remote steering commands or a mayday message will be more critical than an informative warning from the machinery, hence calling for stricter requirements. Requirements to redundancy of communication channels and equipment will also depend on the needed reliability and capacity. This may also to some degree be ensured by requirements on appropriate maintenance of the communications equipment. Connectivity can be verified by documentation such as coverage maps (Figure 16) and/or dedicated testing and monitoring of the intended communication link in the geographical area in which the ship is intended to operate. The certification will then be specific to that area.

For a remote control centre, there will be requirements to the way the control centre is designed as well as to the organization managing and operating the control centre, including requirements to the competence of the remote control crew. The aim

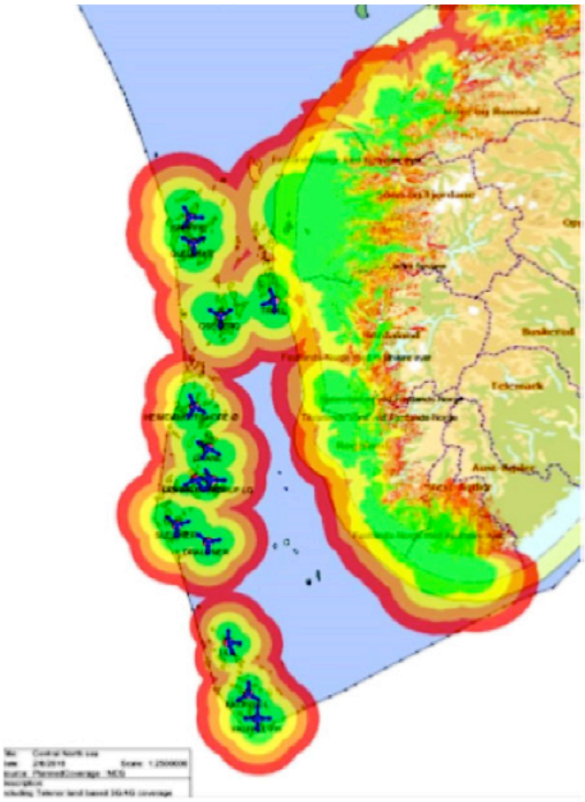

Figure 16: Map describing the quality communications and coverage outside the Norwegian coast

is to ensure that adequate condition analysis and action planning can be achieved by the remote crew to ensure safe operation of the ship.

Requirements to the design of the remote control centre must be linked to its intended scope of operations. For the purposes of efficiency, it has been envisaged that it must be possible to operate several ships from the same control centre. The main task of the operator in this scenario could be to monitor the autonomous operation of the ship and only to actively intervene in the operation should there be an anomaly. This is similar to what is done for dynamic positioning systems of ships today. The challenge for these systems will mainly be related to the way information is presented to the operator, enabling immediate situational awareness supporting an appropriate reaction to the anomaly. The requirements to the organization and operation, including verification procedures, will most likely be based on modifications of existing safety management systems required by the International Safety Management (ISM) Code. DNV GL plans to publish a guideline for remote control and operations centres.

The remote control centre and the operator must be certified in combination, as the qualification of the operator must be linked to the way that information is presented, much like a pilot needing to be certified for a specific type of plane. The training and verification of the remote control centre and its operator can be done in a simulator, but verification should also be carried out at a dedicated sea trial and during operations.

5.2.3 Action control

The requirements for reliability, availability and fault tolerance of the action control system and actuators will likely be higher than to those of a traditional manned ship, where these requirements are linked to the number and qualification of an attending crew. Reliability must be ensured by requirements to the design, operation and maintenance of the control system and actuators. Due to the reduced possibility of carrying out maintenance during operations, a certain level of condition monitoring as well as redundancy may be mandated to maintain a defined reliability level. The verification procedures for the control systems can be based on physical and on simulator-based verification for software intensive systems, but since requirements for automatic fault tolerance increase, simulator-based verification would be more efficient in proving a large set of different fault scenarios. Simulation-based verification needs a digital representation (digital twin) of the system under test that follows the physical equipment through its life cycle. Verification of the functionality of the actuators must be based on tests carried out during commissioning and sea trials. The evaluation of the control system and actuators during operation can be based on surveys and tests. However, it is more likely that the condition of on-board actuating equipment will be monitored continuously through sensors and software as part of a condition monitoring system. This may also build on the recent market trend of servitization, where manufacturers deliver complete ship systems rather than individual components and guarantee the reliability of these systems through alternative maintenance schemes based on condition monitoring, selling the performance of the system rather than only the system itself. The reliability of the sensors in the condition monitoring system should also be assured throughout the lifetime of the ship by means of remote or on-premise testing and inspections. For remote control, requirements to redundancy and maintenance of the communications link must also be defined to ensure the reliability of the control signal communication.

5.2.4 Cyber security

Due to the reliance on software and connectivity, cyber security risk emerges as an issue to be managed for remote-controlled and autonomous ships. For autonomous solutions, there is a risk of people with malicious intents introducing malware or viruses into the situational awareness or decision-making software. This can be done via the communications link to the ship or by other means such as accessing the software at the location of the software vendor. For remote-controlled functions, it could be possible to take direct control of the function by hacking the communications link. The more dependent a ship's operation is on software and communications, the more vulnerable the operation is to these threats. The threat is not limited to the ship's operation; it also extends to the associated commercial operation and operating environment. The maritime industry has already seen the threat demonstrated in recent cyber attacks resulting in huge revenue losses. However, the possible effect of a cyber attack on the safety of the ship's operation becomes increasingly critical when the operational ship functions are controlled by software and control signals sent through a communications link. DNV GL has recently issued a class notation(26) to improve cyber resilience and prevent downtime for ships. However, cyber security risks are not static, and requirements, verification procedures and counter measures must be continuously updated to reflect the developing threat, particularly related to remote-controlled and autonomous ships.

5.2.5 Likely technology implementation

For most applications, it is likely that a combination of algorithms and a remote control or local operator will be handling the situational awareness and decision-making. Such a combination will affect the requirements to both the autonomous and the remote control solution, because they can mutually support and act as redundancy for each other. As an example, for a purely remote-controlled system there will be very stringent requirements to the reliability and quality of the communications link, as a loss of this link will render the ship without control. However, should there also be a robust autonomous system present, this should still provide control of the ship function in the case of lacking connectivity. At the very least, the system should be able to abort normal operations and put the ship in a safe state or a minimum risk condition (MRC), which may be different for different operation modes. The control of such an MRC must be automated and initiated based on a threshold risk for normal operation. This risk mitigation embedded in system redundancies and the availability of minimum risk conditions should be reflected in the requirements to each system, and the assurance scheme should also account for this.
It is also important that companies operating autonomous, remote-controlled and/or remotely supported ships have a Safety Management System (SMS) ensuring that they, in accordance with the ISM Code,:

- provide for safe practices in ship operation and a safe working environment;
- assess all identified risks to its ships, personnel and the environment and establish appropriate safeguards; and
- continuously improve the safety management skills of personnel ashore and aboard ships, including preparing for emergencies related both to safety and environmental protection.

The harvesting, analysis and utilization of information – whether through control centres ashore or through other digital means – must be handled through the SMS. Ensuring that the systems, measures and personnel involved operate effectively is critical.

5.2.6 The DNV GL approach

DNV GL is involved in several research projects in collaboration with leading technology providers, in addition to carrying out research in collaboration with academia on dedicated research platforms such as the ReVolt model (Figure 17). Our goal is to build the competence enabling us to ask for the right proof to assure the safe performance of the ship and its equipment. We are also building new tools with the aim to carry out our own independent testing of algorithms for situational awareness and decision-making. This will enable us to define our own scenarios for which we can evaluate the algorithms. Not disclosing these scenarios and having the possibility to change the scenarios will give added confidence in the safety performance of the algorithms passing the tests. Any software updates will also have to be subjected to this test. In addition, the system and equipment will be subject to specific verification tests during commissioning of equipment and after commissioning of the ship. Continuous monitoring of the safety performance of the autonomous and remote-controlled systems during operation may also be required in the form of an alternative survey scheme by requiring specific information from the systems. A guideline, giving a detailed description of the suggested classification process for remote-controlled and autonomous ships, is being released in parallel with this position paper.[27)]

A significant effort will be required to build, maintain and operate the classification scheme indicated above. DNV GL firmly believes that this is necessary to ensure the safe implementation of remote-controlled and autonomous ships, but the approach depends on the regulators and industry agreeing that this is the required level of assurance. The simplest option for independent verification organizations, such as classification societies, to provide safety assurance of these new technologies would be to adopt a process assurance approach. This will only assess whether the technology or service provider is following the required procedures and standards, and give a limited level of confidence in the safety of the system implementation. DNV GL believes that to provide the necessary confidence in these new and potentially hazardous ways of operating ships, it is necessary for the verifying organization to carry out assurance also on the product and the service itself. Such product assurance requires expert knowledge and tools.

Should a process assurance regime be accepted as sufficient by regulators and the industry, it will be difficult for individual organizations to maintain a product assurance scheme in a competitive environment. Competition on safety standards and verification procedures may then lead to implementation of solutions that are not safe.

Figure 17: The ReVolt model being used as a dedicated research platform in collaboration with NTNU

6 MOTIVATION

If technology solutions related to autonomous and remotely controlled ships are to be adopted and scaled, there needs to be sufficient motivation for implementation. The main factor influencing the rate of uptake will be whether the technology offers a cost effective way of fulfilling the mission of a ship, but other factors such as the effect of the technology on ship emissions can also serve to motivate this.

6.1 BUSINESS CASE CONSIDERATIONS

Introducing technology for supporting the safe operation of ships with a reduced crew may prove to have a positive impact on safety, but such solutions will only scale if there is a good business case supporting them. In short: if the technology provides a solution that is more cost effective and equally reliable, safe and sustainable to current solutions, there will be a demand in the market for these technologies. The business case is, in a simple form, a function of cost and revenue.

The costs can be divided into capital cost, operating cost and voyage cost.

6.1.1 Capital cost

The capital expenses include costs associated with financing and depreciation. The factors influencing these costs, which can be affected by the reduction or removal of crew are the cost of the asset which, in turn, affects the size of the loan, expected salvage value and estimated useful life. The cost of the ship will be significantly affected by reducing or eliminating the crew, but this will completely depend on the type of operation and the magnitude of the crew's reduction. For a fully unmanned ship, there will be limited costs associated with structures and systems for sustaining people on board the ship. On the other hand, there will be cost increases due to the technologies that are introduced to replace the human operator in the form of sensors, software, communications systems and actuators. Stricter requirements to monitoring and redundancy for improving the reliability of systems such as machinery and communications will also increase costs. New elements such as remote control centres will also contribute to increasing costs.

The big question is whether the total cost of an unmanned ship will be higher than that of a conventional manned ship. This is very much dependent on the type of ship, but in the beginning, it is likely that an unmanned ship will be more expensive due to risk mitigation measures associated with the technology implementation. These risks will mandate strict requirements from a variety of regulators and continuous development by the system vendors driving up the price. However, as experience is gained, the requirements may be loosened and costs of systems reduced as they are commoditized and scaled. Eventually, the capital costs may then be lower than for an equivalent conventional manned ship.

To evaluate the effect on salvage value and useful life, it is necessary to distinguish between the traditional assets, such as the hull and the machinery, and the novel assets, such as the sensors and software. The expected useful life of the hull and machinery can be longer than today if they are well maintained through a condition-based maintenance approach. The lifetime of the hull is currently closely linked to the other ship functions, and useful life will depend on the total condition of the ship. This will also be the case for autonomous and remote-controlled ships, but here the sensors and software could more easily be updated to modernize the ship. If the hull is then fully functional, its lifetime can be prolonged. The machinery will also likely have a longer lifetime because there will be stricter requirements to condition monitoring and robustness. On the other hand, the lifetime of the sensors and software may be much shorter than the lifetime of the ship itself as explained above. The salvage value will depend on when the residual value is realized in the ship's life cycle. As a second-hand asset, the value of an autonomous ship can be higher than for a traditional ship, since much of the value is embedded in the ship's intelligence, which can be continuously modernized by software updates. The scrapping value of the ship may be reduced, as there will probably be less material such as steel to recover.

6.1.2 Operating cost

The operating costs of a ship can roughly be divided into costs associated with crew, stores, repairs and maintenance, insurance and administration. Crew cost will clearly be affected by the size and competence of the crew. Even for ships where the total number of crew is not reduced, technologies intended for reducing the crew can enable a less qualified crew and therefore reduce costs. For ships with reduced or no crew, the aspect of remote monitoring and control is central, and the costs associated with crew in a remote control centre must also be accounted for. To gain cost benefits on crew, the total crew cost required to support operations on board and on shore must be accounted for.

The cost of stores is related to consumables required for the day-to-day operation of the ship. On the cost side, the stores mainly consist of lubrication oils required to operate the on-board machinery. For a ship with reduced manning, lubrication will still be required if the ship has rotating machinery, but the storage location may be affected as this may no longer be on the ship. Costs related to consumables such as food intended for sustaining the on-board crew will obviously be reduced by reducing the size of the attending crew, but such costs may also be incurred for a crew in a remote control centre.

Costs related to planned repairs and maintenance for the ship hull may not be significantly affected, but for systems and components it will depend on their robustness and complexity. There will be equipment that is no longer needed, because it was associated with sustaining people on board, but there will also be additional equipment required to carry out the functions previously carried out by the crew. Some of this equipment will also likely be on shore in connection with a remote control centre. The likely requirement for robustness and comprehensive condition monitoring of autonomous and remote-controlled equipment will likely decrease the costs related to planned maintenance and repairs, but a traditional ship with the same level of robustness and condition monitoring will have the same benefits. Any increase in safety will also have the potential to reduce costs associated with unplanned repairs after accidents.

The cost of insurance for remote-controlled and autonomous ships will be closely linked to the effect on risk as compared to that of a traditional ship. The regulations will probably, by definition, not accept an increased risk level. The total cost of insurance may therefore decrease. The effect on the various insurance policies will depend on evidence of reduced risk. Initially, one could even experience higher premiums due to uncertainties related to the risk level.

Ship management is comprised of several functions such as crew management and technical management. The management of crew will clearly be affected by the reduction or elimination of crew, and as such the administrative costs related to crewing will be affected. However, even with the elimination of an on-board crew there may be management costs related to on-shore crew engaged in operations and crew for maintenance and repairs activities. The costs related to technical management may also be affected depending on the effect of autonomy and remote control on the ship's operation and technical performance and operation of the ship equipment. One interesting aspect which is brought forward by remote-controlled and autonomous ships is whether traditional ship management companies will be the ones operating the ships. These companies are not yet set up for managing and operating remote-controlled and autonomous ships, and the competence required for operations may be different than for traditional ships. There is already evidence of companies adjusting to the technological development by the formation of management companies such as Massterly, a joint venture by the technology provider Kongsberg and the ship management company Wilhelmsen, intended to specifically manage remote-controlled and autonomous ships.

6.1.3 Voyage costs

The voyage costs of a ship are linked to the variable costs of a journey such as fuel, port dues, pilots and canal fees. The effect on fuel or energy cost will completely depend on the ship type and operation and is discussed below. The costs associated with port fees may change depending on the existence of a crew in attendance. An unmanned ship will challenge the port infrastructure with respect to docking/undocking, mooring and cargo handling, and required developments of port infrastructure to accommodate this could probably affect the port fees for such ships. The costs for pilotage will likely also be affected. An unmanned ship with no provisions for people on board would obviously not be able to accommodate a pilot in the traditional sense, but one could envisage that a pilot could support the control of the ship from the remote control centre of the ship or a dedicated monitoring centre for the responsible area of the pilot. If the reliability of the autonomous or remote-controlled navigation system is proven, one could question the need of a pilot at all. A new variable cost item that could prove to be significant for remote-controlled ships is the cost of transferring information from the ship and control signals back to the ship. This cost will depend on the amount of data transfer required and the cost associated with the communications carrier transferring this information.

6.1.4 Revenue

The revenue of the operation depends on the type of charter contract and the associated charter rates. In turn, the type of charter contract depends on the type of ship and its operation. As an example, the revenue of a container ship will be based on the freight rates obtained for the cargo. This is typically defined as the price at which certain cargo is delivered from one point to the other. The parameters that can affect the revenue of a container ship are therefore typically related to the type, volume and weight of the cargo transported and the speed at which the cargo is transported. Reducing or eliminating crew will free up more space to be used for containers by stacking containers where the wheelhouse is normally located and avoiding the typical reduction in container stack height towards the bow of the vessel. For a small container feeder vessel, the additional container slots could add up to approximately 20%,, but this percentage will decrease with size. However, these additional slots are with reduced stack weight and, therefore, less valuable than slots below deck. In addition, assuming constant deadweight tonnage, the additional cargo mass which can be transported is relatively small since only the mass of the deck houses and crew support systems can be considered as compensation.

The speed of the ship is independent of crewing, but eliminating manning could accommodate reduced speeds, as for such a ship the crew cost will not be a factor influenced by the speed. Reduced speed would also lead to reduced energy requirements (see below), but reduced capacity and revenues. This would have to be compensated for by building more ships,

Figure 18: Ship without a ship bridge

which, in turn, would impact the capital costs, but a study carried out by DNV GL[27)] shows that the savings in fuel costs would still give an attractive business case.

Assuming the autonomous and remote-controlled solutions will provide improved safety and reliability, this will increase the availability of the ship, which, in turn, will increase revenues due to higher charter income. Being able to demonstrate increased availability will also make the ship more attractive to charter parties.

It is difficult, if not impossible, to quantify a generic business case for remote-controlled and autonomous ships at this stage because all the elements of the business case are not defined and because most of the elements that are defined are not quantifiable. The business case will also be completely dependent on the type of ship, type of operation and size of ship as well as on the eventual requirements set by the regulatory regime. The commercial aspect will become clearer after some demonstrators have been built and operated for some time.

6.2 FUEL CONSUMPTION AND EMISSIONS

The effect on fuel consumption and the associated emissions of remote-controlled and autonomous ships will also be an important factor affecting the societal acceptance and possible uptake of the technology.

Energy requirements of a ship are a function of the energy needed to carry out the various operations required to fulfil the mission profile and the efficiency at which this energy can be produced. Associated emissions will depend on the energy source that is used to provide this energy. The energy requirements for a ship can typically be divided into the energy required for ship propulsion, the energy required for sustaining people on board and the energy required for on-board operations.

6.2.1 Energy required for ship propulsion

The energy required for ship propulsion depends on parameters such as ship resistance and efficiency of the propulsion train.

The ship resistance is primarily affected by the ship speed, shape and draft, in addition to environmental conditions such as wind, waves and current.

The level of manning of a ship does not directly affect the ship speed, but it could affect the logistics chain and the acceptance for reducing the speed. In the DNV GL ReVolt project[28)], it was suggested that a ship speed of 6 knots be adopted for an unmanned container ship. To compensate for the reduction in transport capacity, more ships were deployed for the same route. Following this line of reasoning, it was found that two ships operating at 6 knots would consume 30 to 50% less energy than one ship operating at 12 knots, depending on design and environmental conditions. Such a philosophy could also be adopted for manned ships, but this may be prohibited by the increase in operational costs caused by the requirements for more people at sea for carrying out the required transport work. It should also be noted that this philosophy will have logistical challenges for some trades and operations, particularly if transport time per asset is critical.

The shape of the ship is dependent on the required volume and design. The required ship volume can be decreased by reducing or eliminating the manning, as some of the space on a traditional ship is used for sustaining the people on board the ship. The relative impact of this on the total ship volume depends on the ship type and operation. For a large ship with a small crew, the relative effect will be small, whereas for a small ship with a large crew, the effect will be substantial. The shape of the ship may also be affected by different design constraints. There are several design constraints for a ship which are related to the accommodation and well-being of the people on board. Changing or eliminating these constraints could lead to more optimized designs for fulfilling the mission profile of the ship, reducing the energy requirements. One example of this is the removal of the ship bridge (Figure 18). This will lead to a reduction in wind resistance.

The ship draft is a function of the ship weight. As for the volume, this will be affected by the requirement to design and by the equipment for supporting the people on board the ship. The relative effect of this on the draft will, for the most part, depend on the deadweight of the ship. For a ship carrying high density cargo, the impact will be marginal, but for the same ship in unloaded condition, the effect of reducing the weight will be more substantial.

The efficiency of the propulsion train can also be influenced by the manning level. On the negative side, safety requirements may mandate redundancies in the propulsion train, which can limit the adoption of single-screw direct-coupled propulsion trains, the most efficient form of propulsion for large ships today. On the positive side, changes to design constraints of issues such as noise and vibrations can allow for the design of more efficient propellers.

6.2.2 Energy required for sustaining people

It is obvious that reducing manning will reduce energy demands for sustaining the people on board the ship. Again, the relative effect of this will depend on the type of ship and operation. For large bulk carriers, the energy need for propulsion can typically approach 95% of the total energy required to operate the ship27). Removing the energy required to sustain the manning will therefore have a marginal effect on the total energy requirements. However, for some other ship types such as offshore supply vessels, the energy required for propulsion may only represent as little as 50% of the total energy requirement. The rest is divided between auxiliary power requirements for sustaining the on-board crew and for supporting other ship functions. In this case, the reduction of crew can therefore have a significant impact on the total energy requirement of the ship. It should be noted that even if the relative savings are high for the supply vessel compared to the large bulk carrier, the absolute savings can be higher for the bulk carrier.

6.2.3 Energy required for on-board operations

The energy requirements for supporting other ship functions are again related to the ship type and operations. Reduction of manning may increase the energy requirements associated with these functions, as some of them will require automation, which requires energy-consuming technology. However, they may also lead to reduced energy requirements. As an example, automatic mooring systems will lead to an increase in energy consumption on shore, but could reduce the requirements for ship manoeuvring, and therefore reduce the energy consumption on board.

6.2.4 Ship utilization

Another way of reducing the energy requirements for carrying out a function such as transporting goods is to increase the utilization rate of the ships used. This has received a lot of attention for autonomous cars, because utilization rates for cars, and particularly private cars, are very low. However, for most merchant ships the utilization rate is rather high. The potential for increasing the utilization rates may therefore be limited, but the potential needs to be explored on a case-by-case basis. For example, a commuter ferry which today is operating during limited periods of the day could feasibly operate 24 hours a day if the ferry operation was made fully autonomous. This would provide a significant improvement in service to the customer.

6.2.5 Emissions

The emissions from ships are closely linked to the energy requirements. A reduction in energy requirements would therefore also reduce the associated emissions. Emissions could also be reduced by introducing alternative fuels. Although there is no direct link between reducing the crew and alternative fuels, many of the alternative energy carriers that has the potential for reducing ship emissions are associated with challenges related to low energy density. This is the case for fuels such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG), and for energy carriers such as hydrogen and batteries. The additional space created by reducing the crew could therefore be allocated to accommodate the alternative energy carrier. In addition, the alternative energy carriers can be more acceptable from a safety perspective, since many of them can pose direct hazards to people on board the ship. Indeed, the combination of autonomous and remote-controlled ships and alternative energy solutions such as batteries may prove to be a perfect match, since battery electric solutions are very robust and require limited maintenance28).

7 SOCIAL AND ETHICAL CONSIDERATIONS

Remote-controlled and autonomous ships could arguably be the most disruptive development in shipping since the introduction of the diesel engine in the early 20th century. This new technology-driven way of operating ships has the potential to not only disrupt the entire business model of the shipping industry, but also the role of shipping in society. A transition towards increased automation on ships controlled by algorithms or a remote crew, reducing or eliminating the crew in attendance, has substantive societal and ethical consequences. Given that this trend is driven primarily by efficiency and costs savings, the consequences need to be carefully identified and considered to ensure the digital transformation in the maritime sector is also driven by safety and responsibility concerns. In this section, we give a very high-level overview of some of the key social and ethical issues that emerge.

The substitution or substantive reduction of crew with digital technologies may represent a loss of jobs. At the same time, new experts will be needed to operate and maintain the new digital systems integrated in the ships. Although it is difficult to foresee the potential job losses and emerging job creation, it is clear that the integration of digital technologies into shipping is likely to lead to an unequal impact on different societal groups and regions, given that the competence and location of these workers will be different from what is required today. For nations and companies providing seafarers serving in traditional ship operations, remote-controlled and autonomous shipping will probably be seen as a threat. For nations and companies providing the competence and technologies needed to operate remote-controlled and autonomous ships – such as sensors, reliable connectivity and the capacity to process and store data – this will likely lead to job creation. Services related to alternative maintenance schemes and mechanical assistance on shore, tasks that were earlier performed by crew while at sea, will also be in demand. These support functions will generate new employment and innovation opportunities, but it is likely that such jobs will move towards highly developed regions with mature technological capabilities and trained staff. It is important to note that more than half of the world population still has no access to Internet services[29)], thus there are regions and social groups without the capabilities to take advantage of the new possibilities emerging. This means remote-controlled and autonomous shipping is likely to deepen existing inequalities across social classes and countries unless measures are put in place for technology transfer, social protection, and reskilling of crew.

There is an additional set of ethical issues related to the potential disappearance of seamen. A ship's crew provides many functions besides the technical and professional tasks they perform on ships. Seamen are a professional community with specific skills, histories, societal roles, cultural functions, and value systems in all regions of the world. The loss of attending crews on ships is thus not only the loss of skills, but the loss of culture, community and ethical values. These non-technical dimensions will play a central role in the public acceptance of remote-controlled and autonomous ships. Trust in technologies emerges when these technologies are perceived to reflect widely accepted ethical principles. But we tend to associate these principles with human action. The cultural loss of the figure of a seaman or a captain makes it less likely to ascribe moral agency to a technology that has made such cultural icons redundant and thus will lessen the opportunities for trust in the application of emerging digital technologies to shipping.

Giving machines authority to make decisions that were previously made by human beings is indeed rapidly emerging as a key topic discussed in the philosophy of technology and ethics fields. Traditionally, we have always ascribed responsibility to human agents or to organizations considered legal entities, such as a shipping company. It is difficult to ascribe responsibility for wrongdoing to an algorithm when it is not considered a moral or a legal agent. This challenge is widely discussed in relation to the automotive industry. The debate on the safety of self-driving cars includes the testing of traditional examples of moral dilemmas[30)]. Although intellectually interesting, examples of moral dilemmas such as the trolley problem have only a limited practical impact regarding the construction of safe and responsible algorithms, and, eventually, of AI-controlled vessels and vehicles.

Technology companies are themselves concerned with societal and ethical issues, attempting to identify how to mature safe and responsible intelligent systems. For example, in a recent study, the Microsoft research department argues that trust in AI "will require creating solutions that reflect ethical principles that are deeply rooted in important and timeless values"[31)].

They propose the values of fairness, reliability and safety, privacy and security, inclusiveness, transparency and accountability as the guiding principles for the maturing of AI solutions. Although it may be feasible to introduce such principles into the programming of deterministic algorithms, often referred to as weak AI, it is difficult to see how they can be guaranteed in the case of self-learning algorithms, or strong AI. In this case, programmers will have to extrapolate complex and distant potential societal consequences. These self-learning algorithms would have to think like a human engineer concerned with ethics, not just be a product of ethical engineering[32]. Furthermore, these ethical principles will need to be incorporated in the further maturing and design of autonomous shipping, and translated into the context of the application, raising ethical issues beyond those associated with computer programing. This means, for example, the guiding ethical principles need to apply not only to the functioning of the digital systems in the ship but to the wider operating system.

We have outlined in earlier sections how remote-controlled and autonomous shipping requires a network of agents, a wider system, to enable its operations, given that an autonomous ship will likely be monitored and have facilities for interaction with a remote control centre. The ISM Code (SOLAS Chapter IX) requirements to identify a legal entity (the company) responsible for the safe operation of ships and pollution prevention will remain. This legal entity will have to have a Document of Compliance (DOC), issued by a flag state or a recognized organization on their behalf so they will be easily identified. The dilemmas may arise from ships being operated beyond the legal jurisdiction of the port and/or coastal state.

Adding more stakeholders and complex systems will, of course, complicate matters, especially for the company or DOC holder, who will have to implement or strengthen their SMS in order to handle challenges and utilize opportunities. One would need to clearly identify the players and their tasks, and ensure that all parties are delivering in accordance with requirements. The liability issues will be rather complex, and it is important that parties involved clarify such responsibilities. Dialogue with insurance providers and legal expertise is advisable. Ascribing responsibility and liability is always much more difficult when decisions cannot be directly traced to a single agent. However, assigning accountability can gradually be more challenging with increasing degrees of authority given to the autonomous decision algorithm (higher level of autonomy). Another ethical challenge emerges in relation to the complex chains of decision-making that entail interaction between algorithmic functions and human decision-making. These human–machine interactions will pervade the operation of autonomous ships, and are one of the defining features of remotely operated ships. There will always be a tendency to ascribe accountability to the human player in these interactions, potentially acting as a deterrent for filling in such positions.

There is another category altogether of societal impacts associated with the introduction of remote-controlled and autonomous technologies in the maritime sector. It will lead to profound impacts on the exploration of a common good: the oceans. Until now, the exploration of the ocean space in terms of resources has been mainly limited to fishing as well as oil and gas extraction. Some developments have also been seen within aquaculture, offshore wind, and deep-sea mining. The main barrier to the large-scale deployment of a number of ocean industries is the prohibitive costs associated with construction and operation. These costs are so high because sustaining people in potentially hostile environments is prohibitively expensive, unless the financial returns can defend this investment. Remote-controlled and autonomous technologies for supporting the commissioning and operation of ocean-related industries have the potential to significantly reduce the costs by minimizing or eliminating the requirement of people living and working on or below the sea surface. Such a development is already seen in the oil and gas industry by the trend towards subsea extraction and the processing of oil and gas by means of automation and remote control rather than large manned floating and fixed installations. This technological potential may, however, come with serious negative environmental consequences, particularly because the technologies are ahead of public and private regulation. As indicated, a large majority of the current maritime safety regime is concerned with the performance of professionals, whereas a large portion of the technical requirements is assured by private governance actors, namely classification societies. A new generation of assurance services needs to emerge, adding to current technological considerations of the digital technologies. This creates new risks; thus, the emerging societal consequences and ethical challenges must be a component of these emergent governance regimes.

Autonomous, remote-controlled and potentially unmanned ships have really caught the imagination of the maritime industry. They are interesting developments from a technology point of view and potentially the major disruption to the maritime industry since the 20th century. The technology clearly has the potential to reduce or even eliminate manning on ships, but it is not evident from a safety, sustainability, commercial and societal perspective that this will always be the better solution. It is therefore our opinion that there will be, for the foreseeable future, a role for both conventional manned ships and a large variety of ships with different levels of integrated digital systems and autonomy. Perhaps the most interesting aspect of this technological development is the potential effect it may have on business models, on reshaping the maritime industry and on society in general. Understanding all these dimensions and their interconnections will be very important for anyone who wants to be successful in the maritime industry of the future.

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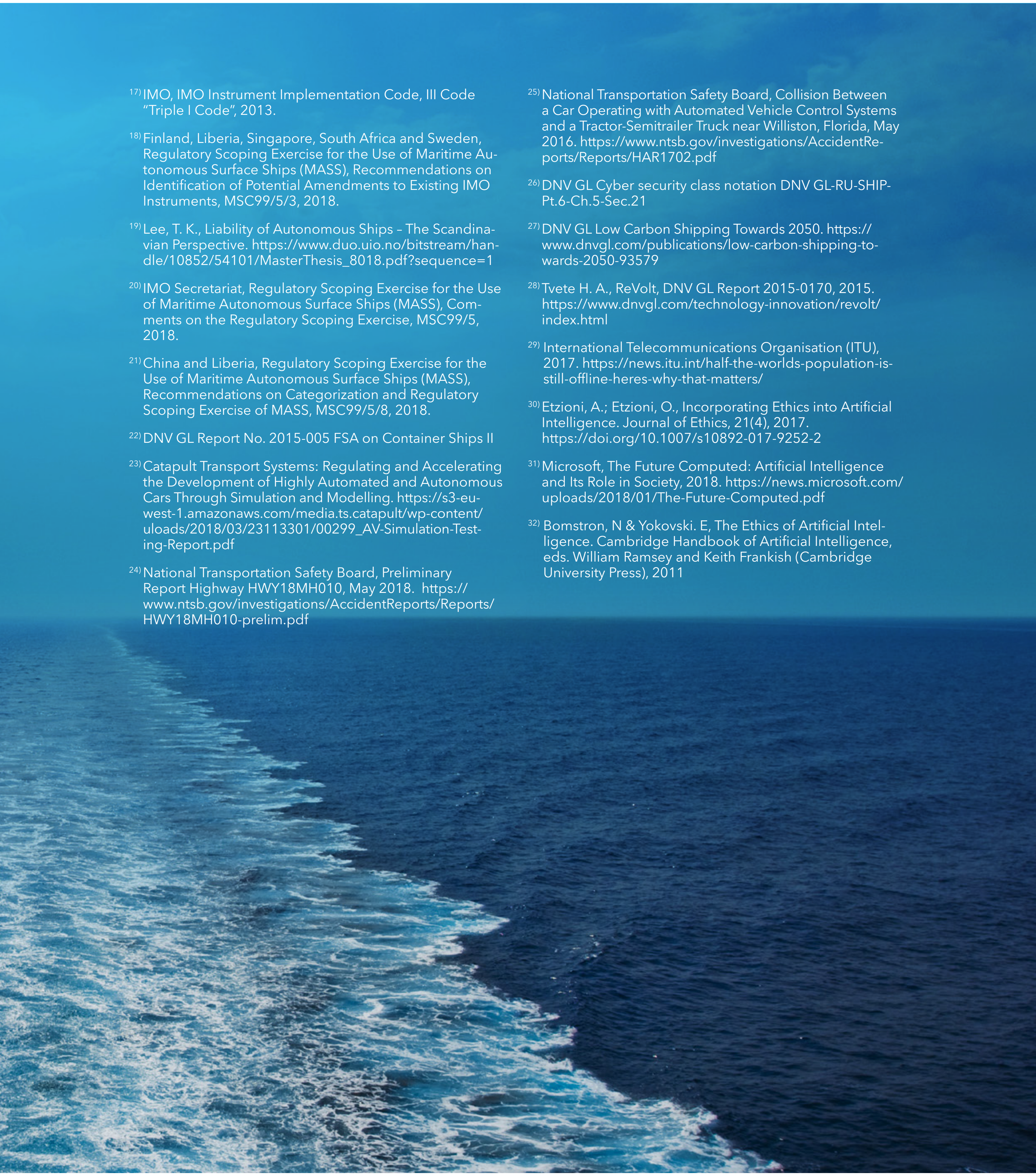

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