Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review

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Abstract - Background: While numerous studies have been carried out regarding the safety of merchant maritime autonomous surface ships, no prior systematic review synthesising their results exists. Objective: Systematic review of peer-reviewed journal articles to collect all safety challenges for merchant maritime autonomous surface ships identified therein. Data Sources: Four databases –SCOPUS, Academic Search Elite, ScienceDirect and Web of Science – were utilised to search for relevant studies. Results: The review has identified three main groups of challenges, namely technological, human factors and procedural challenges. Conclusion: Further research is necessary in order to overcome the identified challenges. The qualitative nature of the collision regulations requires further research in order to ensure autonomous ships comply with legal requirements that are worded in a way that makes them open to interpretation.

Keywords
Autonomous; Challenges; MASS; Ship; Systematic Review; Unmanned; Vessel.

INTRODUCTION
Maritime Autonomous Surface Ships (MASS) – provisionally defined as ships “which, to a varying degree, can operate independent of human interaction” (Maritime Safety Committee, 2019) – have received a lot of attention in recent years. However, most of the research carried out on the topic has been focused on overcoming the technological (Banda, Ahola, Gelder, & Sonninen, 2018) and legal challenges involved (International Maritime Organization, 2018), leaving a research gap in how these vessels can safely be operated.

This review aims to summarise the safety challenges for MASS identified in previous research. The summary can be utilised by researchers to get an overview of the research gaps existing in the field, thereby facilitating the process of finding suitable measures to ensure safe operations of MASS.

METHODS
This paper is a systematic review of journal articles discussing safety challenges for MASS.

Study Design
This review was designed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009) as a guideline. A copy of the review protocol can be found in (Dreyer, 2018).

Search Strategy
The literature search was conducted using the databases SCOPUS, Academic Search Elite via EBSCOhost, ScienceDirect, and Web of Science. The search strings defined in Table 2 were run on 19 September 2018 in as many fields as the different databases allowed. Literature found by running these search strings was complemented by literature found by searching through their reference lists and bibliographies.

Selection Process
Papers were selected according to the inclusion/exclusion criteria defined in Table 1. Figure 1—based on the PRISMA four-phase flow diagram (Moher et al., 2009)—is utilised to highlight the selection process used in this systematic review, which was carried out by the main author of this review.

Table 1. Inclusion and exclusion criteria.

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Published in or after 2008</td>
<td>Published prior to 2008</td>
</tr>
<tr>
<td>2. Published in English</td>
<td>Published in a language other than English</td>
</tr>
<tr>
<td>3. Article published in a peer-reviewed journal</td>
<td>Article not published in a peer-reviewed journal</td>
</tr>
<tr>
<td>4. Full text copy of article available</td>
<td>Full text copy of article not available</td>
</tr>
<tr>
<td>5. Article focuses on MASS and challenges related to their safety</td>
<td>Article does not focus on MASS and challenges related to their safety</td>
</tr>
<tr>
<td>6. Search terms were used in the setting/for the meaning they were intended</td>
<td>Search terms were used in other setting/for other meanings</td>
</tr>
<tr>
<td>7. Non-duplicate study</td>
<td>Duplicate study</td>
</tr>
</tbody>
</table>

After the completion of the selection process, the 14 studies presented in Table 4 remained and were included in the qualitative synthesis.
Table 2. Search strings and results in four databases.

<table>
<thead>
<tr>
<th>Database</th>
<th>Search string</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCOPUS</td>
<td>( ALL ( ship* OR (( vessel* OR vehicle* OR craft* ) AND ( maritime* OR marine* OR sea OR ocean ) ) ) AND ( autonom* OR unmanned OR automat*) AND ( merchant OR cargo ) AND ( safe* ) AND ( manag* OR overcom* OR challeng* OR system* ) ) AND PUBYEAR &gt; 2007 AND ( LIMIT-TO ( LANGUAGE , &quot;English&quot; ) ) AND ( LIMIT-TO ( SRCTYPE , &quot;j&quot; ) )</td>
<td>779</td>
</tr>
<tr>
<td>Academic Search Elite via EBSCOhost</td>
<td>(ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime OR marine OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND safe* AND (manag* OR overcom* OR system* OR challeng*) AND (merchant OR cargo)</td>
<td>91</td>
</tr>
<tr>
<td>ScienceDirect</td>
<td>(ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime OR marine OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND safe* AND (manag* OR overcom* OR system* OR challeng*) AND (merchant OR cargo)</td>
<td>43</td>
</tr>
<tr>
<td>Web of Science</td>
<td>&quot;TS=((ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime OR marine OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND safe* AND (manag* OR overcom* OR system* OR challeng*) AND (merchant OR cargo))Refined by: LANGUAGES: ( ENGLISH )Timespan: 2008-2018. Databases: WOS, KJD, MEDLINE, RSCI, SCIELO. Search language=Auto &quot;</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 1. Flowchart of the selection process used in this systematic review.

Data Extraction
Data from the reviewed articles were manually extracted by the main author of this review. Principal data including author, year, title, country, design and outcomes are summarised in Table 4 below, while the identified safety challenges for MASS are discussed in more detailed in the results chapter.

Synthesis of Results
A narrative synthesis according to the guidance from Popay et al. (2006) was utilised in this review. The outcomes of the included studies and their methodological adequacy were described, explored and interpreted and when similarities emerged, they were be categorised as themes with explanations (Enya, Pillay, & Dempsey, 2018).

Quality Appraisal
The methodological quality of the identified studies that met the inclusion criteria were critically appraised using a set of screening questions utilised by Gillman and Pillay (2018), which were adapted from the Critical Appraisal Skills Programme (CASP) (Critical Appraisal Skills Programme, 2018).

The results of the quality appraisal and the risk of bias assessment can be obtained from (Dreyer, 2018).

RESULTS
Table 3. Main groups of challenges with sub-groups.

<table>
<thead>
<tr>
<th>Main Groups</th>
<th>Sub-Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological</td>
<td>1. Hardware</td>
</tr>
<tr>
<td></td>
<td>1.1. Sensors</td>
</tr>
<tr>
<td></td>
<td>1.2. Communication</td>
</tr>
<tr>
<td></td>
<td>1.3. Fire Safety</td>
</tr>
<tr>
<td></td>
<td>1.4. Mooring</td>
</tr>
<tr>
<td></td>
<td>2. Software</td>
</tr>
<tr>
<td></td>
<td>2.1. Decision System</td>
</tr>
<tr>
<td></td>
<td>2.2. Software Errors</td>
</tr>
<tr>
<td></td>
<td>2.3. Cyber Security</td>
</tr>
<tr>
<td>Human Factor</td>
<td>1. Training</td>
</tr>
<tr>
<td></td>
<td>2. Effect of Technology on Human Operator</td>
</tr>
<tr>
<td></td>
<td>3. Human Centred System Design</td>
</tr>
<tr>
<td></td>
<td>3.1. Migration of Workplace</td>
</tr>
<tr>
<td></td>
<td>3.2. Presentation of Data</td>
</tr>
<tr>
<td>Procedural</td>
<td>1. Undesirable Events</td>
</tr>
<tr>
<td></td>
<td>1.1. Anticipated</td>
</tr>
<tr>
<td></td>
<td>1.2. Unanticipated</td>
</tr>
<tr>
<td></td>
<td>2. Standard Operations</td>
</tr>
<tr>
<td></td>
<td>2.1. Navigation</td>
</tr>
<tr>
<td></td>
<td>2.2. Maintenance</td>
</tr>
<tr>
<td></td>
<td>2.3. Cargo Care</td>
</tr>
<tr>
<td></td>
<td>2.4. Risk Assessment</td>
</tr>
<tr>
<td></td>
<td>2.5. Safety Controls</td>
</tr>
<tr>
<td></td>
<td>2.6. Absence of Regulations</td>
</tr>
</tbody>
</table>
Table 4. Characteristics and summary of reviewed articles.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Title</th>
<th>Country</th>
<th>Design</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acanfora, M., Krata, P., Montewka, J., &amp; Kujala, P.</td>
<td>2018</td>
<td>Towards a method for detecting large roll motions suitable for oceangoing ships</td>
<td>Finland, Poland, Italy</td>
<td>Case study</td>
<td>With the absence of seafarers on board, autonomous ships must have reliable methods for detecting critical operational conditions to be avoided. An alert must be raised when a roll motion starts to develop and an evasive manoeuvre must be executed immediately. This study therefore proposes a method providing for the avoidance of dangerous phenomena involving excessive motions of the ship.</td>
</tr>
<tr>
<td>Ahvenjärvi, S.</td>
<td>2016</td>
<td>The Human Element and Autonomous Ships</td>
<td>Finland</td>
<td>Exploratory</td>
<td>The paper highlights that the introduction of autonomous ships does not mean that there is no more human element involved in the navigation process and explores a number of select human factor issues that could be challenging in the safety management of autonomous ships.</td>
</tr>
<tr>
<td>Burmeister, H.-C., Bruhn, W., Rødseth, Ø. J., &amp; Porathe, T.</td>
<td>2014</td>
<td>Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective</td>
<td>Germany, Norway, Sweden</td>
<td>Exploratory</td>
<td>The development of advanced and integrated sensor systems for automated lookout, autonomous navigation systems incorporating the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) and safe operation in harsh weather, a safe and reliable ship-to-shore communication architecture as well as human-centred design of onshore monitoring stations are regarded as central challenges for MASS.</td>
</tr>
<tr>
<td>Burmeister, H.-C., Bruhn, W., &amp; Walther, L.</td>
<td>2015</td>
<td>Interaction of Harsh Weather Operation and Collision Avoidance in Autonomous Navigation</td>
<td>Germany</td>
<td>Case study</td>
<td>Challenges for MASS identified in this paper include the requirement to decide independently how to react to unfavourable weather conditions and how to avoid collisions in accordance with the COLREGs. It highlights cargo care, the transiting of dense traffic and coastal areas, and the large number of interconnected requirements and dependencies in the system as problematic, meaning that different requirements must not be resolved independently. It further highlights that misbehaviour or negligence of other vessels must be taken into account and that a MASS must be able to realise when a departure from the rules is necessary.</td>
</tr>
<tr>
<td>Ghaderi, H.</td>
<td>2018</td>
<td>Autonomous technologies in short sea shipping: trends, feasibility and implications</td>
<td>Australia</td>
<td>Exploratory</td>
<td>The paper concludes that new skills and competencies are required to design, build and operate unmanned vessels, and highlights challenges in maintenance, compatibility in navigation support systems and cyber security.</td>
</tr>
<tr>
<td>Hogg, T., &amp; Ghosh, S.</td>
<td>2016</td>
<td>Autonomous merchant vessels: examination of factors that impact the effective implementation of unmanned ships</td>
<td>Australia</td>
<td>Exploratory</td>
<td>The paper argues that the belief in complete reliability and trustworthiness of automation on ships is unrealistic. Numerous challenges are identified, including in the area of communications, human impact, legislation and standardisation, procedures, cyber security, and maintenance and prevention of technological failure.</td>
</tr>
<tr>
<td>Man, Y., Weber, R., Cimbritz, J., Lundh, M., &amp; MacKinnon, S. N.</td>
<td>2018</td>
<td>Human factor issues during remote ship monitoring tasks: An ecological lesson for system design in a distributed context</td>
<td>Sweden</td>
<td>Case study</td>
<td>This study came to the realisation that a control centre cannot just copy the design of a conventional ships bridge. Instead, it is argued that ecological interface design should be utilised in order to create a virtual ecology that reflects the constraints in the work domain and supports user-environment coupling.</td>
</tr>
<tr>
<td>Rødseth, Ø. J., &amp; Burmeister, H. C.</td>
<td>2015</td>
<td>Risk Assessment for an Unmanned Merchant Ship</td>
<td>Norway, Germany</td>
<td>Case study</td>
<td>A number of challenges – combined with some possible solutions – were identified in this paper. Hazards related to the interaction with other ships, errors in detection and classification of small/medium sized objects, detection of objects in low visibility, propulsion system breakdown and heavy weather are highlighted as being challenging to the safety management of MASS as no reliable control mechanisms have been identified yet.</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Year</td>
<td>Title</td>
<td>Country</td>
<td>Design</td>
<td>Outcomes</td>
</tr>
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<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Thieme, C. A., Utne, I. B., &amp; Haugen, S.</td>
<td>2018</td>
<td>Assessing ship risk model applicability to Marine Autonomous Surface Ships</td>
<td>Norway</td>
<td>Theoretical review</td>
<td>This paper highlights that there is currently no appropriate risk model for MASS, which is a challenge for their safety management in itself, because a clear concept of risk is necessary to describe, communicate and manage risk.</td>
</tr>
<tr>
<td>Wróbel, K., Krata, P., Montewka, J., &amp; Hinz, T.</td>
<td>2016</td>
<td>Towards the Development of a Risk Model for Unmanned Vessels Design and Operations</td>
<td>Poland, Finland</td>
<td>Case study</td>
<td>The outcome of this paper is that the safety of an unmanned ship as a system is made up of several features, most of which must not be considered separately from others, as the failure of one of the ships’ subsystem can trigger a chain of events leading to potentially catastrophic consequences. This is visualised in the Bayesian network they created, which describes relationships between safety issues pertaining to unmanned vessels.</td>
</tr>
<tr>
<td>Wróbel, K., &amp; Montewka, J.</td>
<td>2018</td>
<td>A method for uncertainty assessment and communication in safety-driven design - a case study of unmanned merchant vessel</td>
<td>Poland, Finland</td>
<td>Case study</td>
<td>The paper allocates levels of uncertainties to risk mitigation measures. Identified areas with particular uncertainties are the involvement of the remote operators, software solutions and the potential for so-called black swans.</td>
</tr>
<tr>
<td>Wróbel, K., Montewka, J., &amp; Kujala, P.</td>
<td>2017</td>
<td>Towards the assessment of potential impact of unmanned vessels on maritime transportation safety</td>
<td>Poland, Finland</td>
<td>Causal</td>
<td>The results of this paper reveal that the likelihood of an unmanned ship being involved in a navigational accident would decrease, while the extent of consequences – particularly from non-navigational accidents – can be expected to be much larger. Numerous challenges to be addressed in order to allow for the safe operation of unmanned ships are identified in the paper.</td>
</tr>
<tr>
<td>Wróbel, K., Montewka, J., &amp; Kujala, P.</td>
<td>2018</td>
<td>System-theoretic approach to safety of remotely-controlled merchant vessel</td>
<td>Poland, Finland</td>
<td>Case study</td>
<td>The results of this study indicate that ensuring the safety of MASS shall consist of executing various controls on regulatory, organisational and technical plains. As most safety constraint violations can be attributed to technical issues, mitigation of many hazards can be achieved by introducing redundancy to safety-critical systems. Examples of areas that are inherently different to traditional ships are navigation, power generation, fuel management, cargo conditioning and fire safety.</td>
</tr>
<tr>
<td>Wróbel, K., Montewka, J., &amp; Kujala, P.</td>
<td>2018</td>
<td>Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels</td>
<td>Poland, Finland</td>
<td>Case study</td>
<td>The results of this paper indicate that software development and validation appear to be the parts of the system that are hampered most by significant uncertainties regarding safety performance. By applying a system-theoretic process analysis hazard mitigation measures were identified that can improve the safety performance of MASS. As a result, this paper highlighted a number of challenges related to their safety management.</td>
</tr>
</tbody>
</table>
The review has identified three main groups of challenges, namely technological (addressed in 13 different reviewed studies), human factors (addressed in 13 different reviewed studies) and procedural challenges (discussed in 13 different reviewed studies). These main groups were further split into sub-groups as shown in Table 3 above.

**Technological Challenges**

This sub-section presents the identified technological challenges, which can be split up into hardware and software.

**Hardware**

This section presents issues relating to the hardware of MASS, specifically to sensors, communication equipment, fire safety installations, apparatus for rendering assistance and mooring systems.

**Sensors**

MASS must be provided with an adequate sensor system capable of measuring a variety of different data available on-board. The importance of relevant sensors becomes apparent when looking at the consequences of their inadequacy. Due to the lack of “first-hand multi-sensory experience of a living person” (Hogg & Ghosh, 2016), a failure in the sensory system of a MASS would lead to it becoming blind, inevitably leading to it being unable to perform safely and efficiently (Wróbel, Montewka, & Kujala, 2018b). Such an inadequacy of the sensor system could be caused by “sensors’ failures, installed sensors’ inability to measure a required feature, unsuitable sensors being installed or their sub-optimal performance” (Wróbel et al., 2018b), which are all risks that must be addressed.

The literature generally distinguishes between sensors for sensing the environment outside the vessel (Burmeister, Bruhn, Rødseth, & Porathe, 2014; Burmeister, Bruhn, & Walther, 2015; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme, Utne, & Haugen, 2018; Wróbel, Krata, Montewka, & Hinz, 2016; Wróbel, Montewka, & Kujala, 2018a; Wróbel et al., 2018b), and sensors that measure the current state of the vessel (Burmeister et al., 2015; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b). The following critical areas in which adequate sensor data must be ensured have been identified: Lookout (Burmeister et al., 2014; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme et al., 2018; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b), external environmental data (e.g. meteorological and oceanographic) (Burmeister et al., 2015; Wróbel et al., 2018a, 2018b), internal stability data (e.g. motion and stress) (Burmeister et al., 2015; Wróbel et al., 2018a, 2018a), and internal system data (Wróbel et al., 2016; Wróbel et al., 2018a, 2018b).

Lookout data refers to any data used for the observation of the sea for hazards, other ships, land, wreckage and distress signals, and is used to prevent collisions and detect persons in distress. When lookout data is combined with external environmental data such as depth readings from the echo sounder, an image of the external environment of the vessel can be constructed. However, to ensure safe navigation, internal stability data must be gathered and analysed as well. By combining external environmental data and internal stability data, dangerous situations that could lead to loss or damage to the ship or its cargo can be either anticipated and avoided, or realised and corrected.

Internal system data refers to data taken from the different internal systems on board, e.g. machinery data, fire sensor data and data to evaluate damage to the ship.

**Communication**

Another hardware challenge related to the operation of MASS is their communication capability. The reviewed literature generally agrees that the communication architecture of a MASS must be safe and reliable and distinguishes between two different types of communication: “Ship-to-shore” (Burmeister et al., 2014; Ghaderi, 2018; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme et al., 2018; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b), and “ship-to-ship” (Burmeister et al., 2014; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme et al., 2018).

The architecture of the communication system of a MASS is critical for both safety and security (Wróbel et al., 2016) and requires specialised systems with sufficient redundancy and backup operations (Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2018a). It must be ensured that MASS are provided with the necessary hardware to ensure reliable communication both with the remote control centre (Hogg & Ghosh, 2016; Thieme et al., 2018) and the monitoring and navigational systems used in ports (Ghaderi, 2018), even in regions where only restricted satellite bandwidth is available (Burmeister et al., 2014).

Means for communication with conventional vessels must also be provided (Hogg & Ghosh, 2016), which may prove to be challenging as this type of communication must be catered to humans on the bridges of the conventional vessels.

The uncertainties in the capabilities of the current technical communication solutions available lead Wróbel et al. (2018b) to conclude that communication – which is considered to be a major part of the whole system – requires further study.
Fire Safety
Depending on the type of MASS, the design of a technical system capable of preventing or handling fires in all possible scenarios was identified by Wróbel, Montewka, and Kujala (2017) to be an extremely difficult challenge. However, as major subsystems of a MASS are heavily reliant on one another, the performance of such a fire protection system has a direct impact on the vessels machinery systems and navigational capabilities (Wróbel et al., 2016). Therefore it is concluded that MASS fire safety must be carefully addressed (Wróbel et al., 2018a).

Rendering Assistance
MASS may find themselves in a situation where they have to assist another vessel. They must be able to assist in the distress response and be able to pick up and accommodate survivors even in the absence of on-board crewmembers (Wróbel et al., 2016; Wróbel et al., 2017).

Mooring
Seven reviewed papers expect MASS to have a crew on board for the port-related activities, including departure and approach (Burmeister et al., 2014; Burmeister et al., 2015; Ghaderi, 2018; Rødseth & Burmeister, 2015; Wróbel et al., 2017, 2018a, 2018b). In case a MASS operator plans to enter port without having any crew on board, special mooring infrastructure must be provided (Hogg & Ghosh, 2016; Thieme et al., 2018). Such mooring equipment must ensure a safe mooring process for both the ship itself as well as any shore personnel involved in the operation.

Software
The identified challenges regarding the decision system of a MASS, potential software errors and ensuring cyber security are presented in this section.

Decision System
A number of challenges have been identified regarding the decision system that will need to be installed on a MASS designed with a navigation automation system. The two challenges that have been discussed the most is the ability of a MASS to avoid collisions with other traffic in accordance with the COLREGs (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016; Man, Weber, Cinbritz, Lundh, & MacKinnon, 2018; Rødseth & Burmeister, 2015; Wróbel et al., 2018b), and the ability to avoid and react to unfavourable weather conditions (Acanfora, Krata, Montewka, & Kujala, 2018; Burmeister et al., 2014; Burmeister et al., 2015; Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel et al., 2017).

The primary challenge is to ensure that MASS operate in compliance with the COLREGs. This has been fundamentally questioned by Hogg and Ghosh (2016) as they consider MASS as being incapable of mimicking the foresight a human navigator has on the bridge of a conventional vessel. As such, it must be ensured that good seamanship practice is replaced by methods and criteria (Acanfora et al., 2018; Wróbel et al., 2018b) sufficient to ensure that MASS can comply with the COLREGs.

While the COLREGs theoretically apply to all vessels upon the high seas (International Maritime Organization, 1972), misbehaviour or negligence of other vessels sometimes results in them not being applied in practice. The decision system of a MASS must therefore be able to avoid collisions with other vessels regardless of whether they follow COLREGs or not (Burmeister et al., 2015; Rødseth & Burmeister, 2015).

Another important part for ensuring safe navigation of MASS is the availability of reliable methods for detecting critical operational conditions that need to be avoided, both while planning the route and while monitoring the vessels progress along it (Acanfora et al., 2018). If a MASS encounters rough weather (Burmeister et al., 2014; Burmeister et al., 2015; Wróbel et al., 2016; Wróbel et al., 2017) or conditions that induce excessive motion and/or acceleration, her safety can be compromised.

It must be ensured that scenarios that can lead to damage of the ship or its cargo are determined both at the route planning stage and during the voyage execution stage (Acanfora et al., 2018). Detection of a potentially dangerous situation during the route planning stage should lead to the route being amended so that potentially dangerous sea areas are avoided (Acanfora et al., 2018), similar to how rough weather is avoided by utilising weather routing (Burmeister et al., 2015; Rødseth & Burmeister, 2015). During the voyage, the identification of a potentially dangerous situation should lead to the execution of mitigation actions, such as a change in course and/or speed and the raising of an alert to the controller (Acanfora et al., 2018).

When looking at the two challenges discussed above (i.e. reacting to traffic and reacting to environmental influences), it is highlighted that they cannot be resolved independently, as the required actions may be contradicting each other at times (Burmeister et al., 2015). Decisions made by one system module will inevitably have an effect on another. An example of such an effect is the need for a new route to be provided by the planning module if the control module of the MASS decides that it is necessary to deviate from the initially planned route (Acanfora et al., 2018). It is therefore essential that a holistic approach is adapted when designing the decision
system in order to ensure the collaboration of the different components of the system (Wróbel et al., 2018b). As the proper functioning of the decision system depends on the quality of the input data (Wróbel et al., 2016), a stage where the quality of external- and sensor data is evaluated must be included in the system. Situations in which the indications of two or more sensors contradict each other must be identified and resolved in order to ensure the safe operational conduct of MASS (Wróbel et al., 2018a).

Further challenges that must be resolved are which action a MASS should take when all available options lead to undesirable outcomes, and ensuring that a MASS can adapt to unforeseen situations (Ahvenjärvi, 2016).

Software Errors
Even though the reliability and efficiency of the software utilised in MASS is of great importance to safety (Thieme et al., 2018; Wróbel et al., 2018b), there is a high probability that software errors will be present in their control system (Ahvenjärvi, 2016). This is considered to be a main risk for MASS (Rodseth & Burmeister, 2015). Proper software development and testing is therefore considered to be critical (Ahvenjärvi, 2016) and the introduction of technical standardisation, certification and inspection of the control system is encouraged (Hogg & Ghosh, 2016). Highlighted challenges are the revealing of software errors that are connected with abnormal situations (Ahvenjärvi, 2016) and the reduction of errors by reducing system complexity (Rodseth & Burmeister, 2015). Due to the presence of control algorithms in a large number of MASS system components, a lot of work needs to be done in this area (Wróbel et al., 2018a).

Cyber Security
Cyber security is considered critical for the safe operation of MASS (Ghaderi, 2018; Hogg & Ghosh, 2016). While virtually all system components are at risk of an attack (Wróbel et al., 2018a), the communication- and the information technology have been particularly highlighted by Ghaderi (2018). As devastating consequences may be expected if a breach in cyber security occurs (Wróbel et al., 2017, 2018b), ensuring the cyber security of MASS poses a major challenge that must be addressed appropriately.

Human Factor Challenges
The second group of identified safety for MASS are those related to human factors. This group is made up of challenges related to training, the effect of technology on the human operator, and human centred system design.

Training
Ensuring that all persons required to work with the new technology are adequately trained is mentioned as a challenge in a six different studies reviewed in this study (Ahvenjärvi, 2016; Ghaderi, 2018; Hogg & Ghosh, 2016; Man et al., 2018; Wróbel et al., 2018a, 2018b). The challenge to ensure proper training is not limited to seafarers (Ahvenjärvi, 2016) and shore-based operators (Wróbel et al., 2018b), but extends to naval architects (Ghaderi, 2018), technicians and engineers (Hogg & Ghosh, 2016) as well. While Man et al. (2018) do not specifically state adjusted training requirements for MASS operators as a challenge, they do highlight that the required competencies of these operators have not been defined in regulations and that not enough research has been carried out on this topic. Hogg and Ghosh (2016) agree that new skills will be required and acknowledge the absence of regulation in this regard, but also highlight the importance of seagoing experience and question how the MASS operator of the future will gain the first-hand experience necessary to become an experienced Master when there are no more opportunities to work at sea.

As the implementation of operational trainings may have a positive effect on the influence humans have on the safety of MASS, ensuring proper training is of utmost importance (Wróbel et al., 2018a).

Effect of Technology on the Human Operator
None of the papers reviewed suggest that the implementation of MASS will remove the possibility of human error altogether, but the effect that humans will have on MASS has been discussed to a different extent. While Burmeister et al. (2015) and Ghaderi (2018) suggest that the introduction of MASS holds the potential to ultimately decrease human error, Ahvenjärvi (2016), Burmeister et al. (2014), Hogg and Ghosh (2016), Man et al. (2018), Rodseth and Burmeister (2015), Thieme et al. (2018), Wróbel et al. (2016), Wróbel and Montewka (2018), Wróbel et al. (2017), Wróbel et al. (2018a) and Wróbel et al. (2018b) argue that human factor issues will continue to be of significant importance in MASS operations.

The reviewed literature identifies a number of challenges related to the human factor that need to be managed in order to ensure MASS safety:

- Automation-induced complacency results in the operator being unable to detect malfunctions in the system, and is directly affected by the training received, the reliability of the system and the workload experienced (Hogg & Ghosh, 2016). If the operating system of a MASS is reliable, it is likely that the operator becomes over-confident in the system and loses vigilance. This negative effect of automation on the human operator has also been
Remote supervisory control may lead to out-of-the-loop syndrome (Man et al., 2018) and together with the lack of human connection to the MASS and absence of cues in an office-like environment may result in limited situational awareness of the remote operator (Ghaderi, 2018; Hogg & Ghosh, 2016; Man et al., 2018; Wróbel et al., 2018a), thereby possibly increasing the likelihood of an accident occurring (Wróbel et al., 2017). Furthermore, this leads to the inability for the operator to take over control in cases where the automation fails (Man et al., 2018) and has caused Hogg and Ghosh (2016) to question the effectiveness of the concept of supervising a MASS from a remote control centre altogether. This question gains more significance because humans are – due to their nature – not suitable for acting as a backup in human-automation interactions (Man et al., 2018).

It is expected that the cognitive demands in the remote control centre will be higher than on the bridge of a conventional vessel (Hogg & Ghosh, 2016). If improperly managed, this may lead to information overload of the controller (Ghaderi, 2018). It is therefore considered essential that operators are kept at optimal mental work load levels (Hogg & Ghosh, 2016). In this regard Man et al. (2018) suggest if the pre-processing of raw data and flow may aid in reducing the demand of an operators cognitive resources.

Another negative side effect of MASS implementation is the skill degradation of those charged with their remote supervision (Hogg & Ghosh, 2016; Wróbel et al., 2018a). Necessary steps must be taken to ensure that the remote operator will retain his or her skills in order to be able to take over control of the MASS when the situation so requires.

### Human Centred System Design

Where the operator of a MASS is not stationed on board, the complete migration of the workspace away from the ship to must be duly considered in the design of the control centre. The presentation of data in a user-friendly way will be a challenge regardless of the location of the operator.

### Migration of Workplace

One of the main results of the work of Man et al. (2018) is the realisation that the ecological changes related to the migration of the working place away from the ship must be considered when designing the remote control centre. The design of the technology in the control centre must be shaped for the new task of remote control and monitoring, meaning that current systems and practices cannot simply be transferred to the new location (Man et al., 2018).

Ignoring the relationship between user and environment when designing the control centre may result in workplaces that are not suited for remote supervisory work and increase the gap between the demands of the work domain and the capabilities of the operator (Man et al., 2018).

### Presentation of Data

A substantial amount of interaction between the MASS and its operators may be required at certain stages of a voyage (Thieme et al., 2018). Adapting a user-centred approach results in presenting the necessary data to the user according to his or her goals, tasks and needs (Hogg & Ghosh, 2016) will likely reduce the chance of him or her misinterpreting the data (Wróbel et al., 2017).

Utilising user-centred design in human-machine interfaces allows the operator to gain and maintain situational awareness (Ahvenjärvi, 2016; Thieme et al., 2018). Furthermore, it must be ensured that the data required by the operator is presented to him or her in all operating conditions, including unanticipated undesirable events. It is in these situations that automation functions may not reveal the true state of the system and provide the least help to the operator (Man et al., 2018). A central alarm management system including prioritisation of issues (Burmeister et al., 2014) may aid an operator in these cases, as he or she may not be able to make decisions due to information overflow and/or bad prioritisation of tasks (Wróbel et al., 2017).

### Procedural Challenges

The final group of identified challenges is related to procedures, which is related to both undesirable situations and standard operations.

### Undesirable Events

MASS can potentially experience undesirable events that have either been anticipated in advance (and therefore have contingency plans in place), or not.

### Dealing with Anticipated Undesirable Events

It has been noted in the reviewed literature that even when considerable efforts are expended into ensuring excellent design and performance of MASS, it is likely that at some point a disaster might occur (Wróbel et al., 2017). A number of anticipated undesirable events have been identified in the literature. It is important that suitable measures will be in place to cope with these contingencies.

- Remote operators of MASS must anticipate the possibility of communication disconnections and ensure that suitable safeguards are in place in order to cope with such a situation (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016; Rodseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel & Montewka, 2018; Wróbel et al.,
Failed-to-safe functionalities that could potentially act as such safeguards have been discussed in (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2018a).

- Ahvenjärvi (2016) identifies the situation of multiple and simultaneous sensor faults as a particularly challenging situation for autonomous ships. In fact, the failure of any of the technological equipment on-board the MASS must be addressed in order to prevent minor technological failures from causing an error chain that may lead to an accident (Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b).
- While the consequences of a marine accident involving a conventional vessel are usually reduced by the actions of on-board crew, an unmanned MASS will have to rely solely on the available technology to respond to an accident (Wróbel et al., 2018b). As operators will be unable to make necessary manual adjustments themselves (Wróbel et al., 2018a), the accident response relies heavily on the ability to anticipate potential accident scenarios in the design stage (Wróbel et al., 2016), as this will decide the response mechanisms that will be provided. While it has been stated that damage assessment and control is likely one of the biggest challenges for MASS, previous studies have not accounted for the possible absence of humans on board when evaluating response options to MASS accidents (Wróbel et al., 2017).

Dealing with Unanticipated Undesirable Events
If a MASS runs into an unanticipated undesirable situation, the operator must be alerted in due time. Suitable alert points must be defined in order to ensure that he or she has sufficient time before the situation develops to a point where nothing more can be done to remedy the situation (Hogg & Ghosh, 2016; Wróbel et al., 2016). Due to the unanticipated nature of the undesirable event, this will be a challenging task.

Regarding the accident response of an unmanned MASS, the presence of black swans – which are scenarios that for some reason have not been analysed – must be anticipated (Wróbel & Montewka, 2018; Wróbel et al., 2018a). As it is next to impossible to account for all potential accident scenarios in the design stage, MASS should be designed in a way that ensures a proper level of resilience (Ahvenjärvi, 2016; Wróbel et al., 2017, 2018b).

Standard Operations
The introduction of MASS will have a considerable impact on a number of standard operations, and numerous procedural challenges to ensuring safe operations of MASS have been identified in the reviewed literature. They have been categorised as challenges regarding navigation, maintenance, cargo care, risk assessment, safety control and absence of regulations.

Navigation
In the case of a MASS controlled or supervised from a remote control centre the following challenges regarding navigation have been identified.

- Utilising the traditional hierarchy of a conventional vessel in a remote control centre may not be suitable. Hogg and Ghosh (2016) argue that assigning the captain as the final decision-maker may not be a suitable solution, as he or she will be out of the loop and have difficulty developing proper situational awareness in an emergency. The shift from conventional navigation to MASS operation must therefore be based on a review of manned bridge procedures (Burmeister et al., 2015).
- The interaction between the operator and the MASS varies depending on the level of autonomy. Procedures must therefore be in place to ensure a safe transition when the operator takes control of the MASS (Wróbel & Montewka, 2018), and that the system and the operator are able to adapt quickly to the new operational mode (Thieme et al., 2018).
- As MASS will continue to coexist alongside other vessels in the foreseeable future, it has been suggested that aspects such as the interactions between conventional ships and MASS must receive more attention in the future (Thieme et al., 2018). One such interaction may be the dangerous utilisation of predictable MASS behaviour by conventional vessels, as humans who have regular contact with automated systems have a tendency to create new and risky habits (Ahvenjärvi, 2016).
- Thieme et al. (2018) argue that current navigational aids are designed to assist human navigators, and argue that further investigation is necessary to assess if they need to be changed in order to facilitate MASS navigation.

Maintenance
The absence of a crew on board an unmanned MASS leads to the realisation that there will be no one on board to carry out maintenance while the vessel is at sea (Ghaderi, 2018; Hogg & Ghosh, 2016; Thieme et al., 2018; Wróbel et al., 2018b), causing a number of maintenance related challenges (Wróbel et al., 2017). A rigorous preventive maintenance scheme must therefore be developed to ensure that no maintenance of ship components is necessary while the unmanned MASS is at sea (Burmeister et al., 2014; Thieme et al., 2018; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b). As non-complex hardware problems can
propagate and cause major problems (Rødseth & Burmeister, 2015; Wróbel et al., 2016) it must be ensured that sufficient backup solutions are available in case of a sub-system failure (Thieme et al., 2018).

Depending on the approach chosen to ensure that no maintenance needs to be carried out at sea, a number of different challenges have been identified in the literature. Hogg and Ghosh (2016), Thieme et al. (2018) and Wróbel et al. (2018b) declare that all MASS components will require extreme reliability. Any maintenance required will have to be carried out in port by specialised personnel (Ghaderi, 2018; Hogg & Ghosh, 2016; Thieme et al., 2018), introducing new implications for both port and ship operators (Ghaderi, 2018). It is even suggested that unmanned MASS will require new propulsion concepts, as conventional diesel engines are in need of frequent maintenance (Thieme et al., 2018).

**Cargo Care**

Current designs of MASS suggest that only cargo with low management requirements (i.e. stable, non-hazardous cargo that requires no maintenance or monitoring during the voyage) will be carried on unmanned MASS (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016). However, this view is not shared across the reviewed literature. Wróbel et al. (2016) can see issues arising from self-heating or self-igniting cargo, which suggests that they assume that such cargoes may be carried on board unmanned MASS. Wróbel et al. (2018b) are more direct assuming that more challenging cargoes can be accommodated if MASS are provided with the right functionalities. It should be noted that even if hazardous cargo was banned from being transported on unmanned MASS, undeclared dangerous cargoes may still end up on board (Wróbel et al., 2017). Safety issues regarding the carriage of hazardous cargo must therefore be addressed (Wróbel et al., 2017).

**Risk Assessment**

A number of the reviewed articles focus specifically on assessing the risk and uncertainty involved in MASS operation and highlight the difficulty in establishing a reliable risk model (Rødseth & Burmeister, 2015; Thieme et al., 2018; Wróbel et al., 2016; Wróbel & Montewka, 2018; Wróbel et al., 2017, 2018a, 2018b). However, a clear concept of risk is necessary to describe, communicate and manage risk (Thieme et al., 2018), and make feasible safety recommendations (Wróbel & Montewka, 2018). A number of key challenges that need to be overcome are outlined below:

- There is a widespread uncertainty regarding MASS in general, which means that reliable information regarding their actual design and operating circumstances is not available (Wróbel et al., 2016; Wróbel & Montewka, 2018; Wróbel et al., 2017). However, such information must be available if a generic and comprehensive risk model for MASS is to be developed (Thieme et al., 2018).
- Risk models in shipping have traditionally been quantified based on accident and incident data. However, due to absence of such data in a MASS context, such an approach is not viable for MASS risk models (Thieme et al., 2018). Furthermore, there is no empirical data pertaining to their performance (Wróbel & Montewka, 2018; Wróbel et al., 2018b), and areas that need special attention in the context of MASS operations have rarely been covered in depth in the literature (Thieme et al., 2018). If this absence of reliable data leads to incorrect assumptions, the assessment may lead to unjustified conclusions and incorrect decisions (Wróbel & Montewka, 2018). Circumventing this problem by utilising an existing model to assess risk is also described as questionable (Wróbel & Montewka, 2018).
- The concept of black swans described previously also has direct effects on the risk assessment models for MASS, as the likelihood of incomplete data leads to uncertain outcomes (Wróbel & Montewka, 2018; Wróbel et al., 2018a).
- Due to a lack of an officially defined acceptable risk level, the outcome of the existing risk models cannot be suitably utilised to assess MASS safety (Wróbel et al., 2016; Wróbel et al., 2017).

**Safety Controls**

Ensuring suitable safety controls systematically from higher organisational levels ensures that hazards are controlled at each point of the system structure (Wróbel et al., 2018a). However, mitigating hazards does not only involve the provision of safe control actions; it must also be ensured that those safety controls are applied at the right time and for the right period of time, and that they are applied in the correct sequence (Wróbel & Montewka, 2018; Wróbel et al., 2018a).

A further challenge is to ensure that safety and cost-effectiveness are suitably balanced (Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel et al., 2018a), as the reduction of cost is one of the most important arguments for MASS (Ahvenjärvi, 2016; Ghaderi, 2018; Rødseth & Burmeister, 2015; Wróbel et al., 2017, 2018a).

**Absence of Regulations**

Due to the absence of a regulatory framework regarding the many aspects involving MASS (Hogg & Ghosh, 2016; Man et al., 2018), it must be ensured that suitable operational procedures are available, relevant training is being organised and that the
maintenance of on-board systems is properly managed (Wróbel et al., 2018a).

CONCLUSIONS
As mentioned in Banda et al. (2018), much technological research has been done regarding MASS. A great example is the push for satellite-based high-speed internet that is being developed by several major companies to reduce the likelihood of communication failure with MASS (Coldewey, 2019). However, with increased availability and reliability on internet communication systems, Ghaderi (2018) has identified cyber security as “the biggest challenge facing the maritime industry”. The likelihood of unauthorised control of the ship can only be drastically reduced if proper design of communications, position sensing and on-board control systems is ensured (Rødseth & Burmeister, 2015).

A very real concern for MASS operations lays in the decision system, with “real-time intelligent algorithms for collision avoidance combining multiple vessel situations, dynamic weather conditions and COLREGs compliance is yet to be developed” (Hogg & Ghosh, 2016, p. 218). This is further complicated as the requirements of the COLREGs are sometimes open to interpretation (Vartdal, Skjong, & St.Clair, 2018). An obvious example of this is rule 6 of the COLREGs, which requires vessels to “proceed at a safe speed” (International Maritime Organization, 1972), without quantifying what is meant by the term “safe speed”. MASS compliance with the COLREGs is therefore reliant on smart methods and criteria (Acanfora et al., 2018; Wróbel et al., 2018b) that have not been developed yet and therefore warrant further research.

Finally the realisation that humans are – due to their nature – not suitable for acting as a backup in human-automation interactions (Man et al., 2018) results in a challenge that need to be overcome if MASS are designed to be supervised from a remote control center.

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