Safety and Reliability – Safe Societies in a Changing World – Haugen et al. (Eds)

Accounting for human failure in autonomous ship operations

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ABSTRACT: Recently, numerous organizations have made progress in developing autonomous ships, motivated by, among other factors, the potential for increased safety. This applies especially to accidents involving human error, as autonomous ships would remove operator role from all or most operations. The reality is that although the human role is reduced, autonomous ships would still rely on operators for supervision, remote control, and involvement in case of a glitch or an unexpected situation. Thus, autonomous ships do not fully eliminate the possibility of human error. In this study, we assess the potential for human error in autonomous ship operations. We analyze an unmanned autonomous ship operation, and through a generic analysis of the interaction between operators working a Shore Control Centre (SCC) and system, we identify possible Human Failure Events (HFE). This provide a starting point for performing human reliability analysis of autonomous ships operation.

1 INTRODUCTION

Important projects have drawn attention to autonomous ships in recent years. The so-called MUNIN (Maritime Unmanned Ships through Intelligence in Network) is currently establishing a concept for an unmanned merchant ship. AAWA (Advanced Autonomous Waterborne Applications Initiative), in turn, investigates challenges in different scientific fields related to autonomous shipping operations (Laurinen, 2016). A third example is the DNV GL ReVolt project, which is a concept developed by DNV GL for an unmanned, zero-emission, shortsea vessel.

One of the motivations for using autonomous ships—common to all autonomous systems in general, concerns the potential for increased safety and reliability. Human error accounts for an important root cause or contributing factor of accidents in a diversity of industries and activities, e.g. 70 to 80% in aviation (Wiegmann and Shappell, 2012), over 80% in chemical and petrochemical industries (Kariuki and Löwe, 2007), over 90% in road traffic accidents (Treat et al., 1979). The maritime activity does not differ from those: the European Maritime Safety Agency points to human error as the triggering factor in 62% of incidents with EU registered ships from 2011 to 2016 (EMSA, 2014). Moreover, statistics on fatal accidents have ascertained that work on deck, for example mooring operations, is 5 to 16 times more dangerous than jobs ashore (Blanke, Henrique and Bang, 2017). Therefore, putting the human operator aside for all (or most part of) operation tasks is believed to avoid accidents (Laurinen, 2016). However, as highlighted by Rødseth and Tjora (2014), human error can still occur in autonomous ships operation.

Current projects on autonomous ships have different views on how they should operate in terms of crew onboard and autonomy level. The Munin project calls for a ship that would be unmanned only on the deep-sea part of the voyage, with a crew onboard for the departure from and approach to port. When unmanned, the ship would be autonomous, but monitored by operators in a Shore Control Center who can take over control of the ship in certain situations. The AAWA project, on the other hand, works with the concept of unmanned ships—i.e., there would be no crew onboard at any time of the voyage, and with dynamic levels of autonomy. This means the autonomy level approach would depend on the state of the vessel and mission being executed. In some cases, such as navigation in the open seas, the ship can be nearly fully autonomous whereas for some parts of the voyage it will require close supervision and decision making, or even full tele-operation from the human operator.

The two concepts above show that, although an autonomous ship would have less interference of a human operator, the human is still part of the operation: they would still rely on a human operator for one of the voyages phases (e.g. departure and docking) or for taking over control in case there is a situation the autonomous system cannot resolve by itself. Therefore, the autonomous ship operations are not free of the possibility of accidents generated or aggravated by human error. The current literature, however, have not deeply focused on the human element when considering autonomous ships' safety. In fact, as pointed out by Parasuraman, Sheridan and Wickens (2000), for autonomous systems in general there is a voluminous technical literature on automation, but a still small (but growing) research base examining the human capabilities involved in work with automated systems.

The potential for human error in autonomous ships can be assessed through a Human Reliability Analysis (HRA). HRA is a technique to assess both quantitatively and qualitatively the human contribution to accidents. Swain and Guttman (1983) define human reliability as the probability that a person (1) correctly performs an action required by the system in a required time and (2) that this person does not perform any extraneous activity that can degrade the system. HRA is thus, in short, a method by which human reliability is estimated (Swain and Guttman, 1983; Swain, 1990).

To be able to perform an HRA it is essential to understand, first of all, how the operators will interact with the system. If autonomous ships will be a reality in years to come, ensuring they are safe and reliable is imperative, and the possibility of human errors cannot be minimized.

The current literature presents some relevant works on autonomous ships containing discussions on human factors topics, mostly pointing out the factors that could affect the operators' decision and actions (Ottesen, 2014; Rødseth and Tjora, 2014; Laurinen, 2016). A more general discussion on these factors, applied to all autonomous systems, can also be found (Parasuraman, Sheridan and Wickens, 2000; Chen, Haas and Barnes, 2007). In terms of identifying the possible human failure events (HFEs) in autonomous ships operations, however, the literature still falls short—and this paper aims to fill in this gap.

The identification and definition of HFEs is can be considered as the starting point of an HRA (Ekanem, 2013). Boring (2014) differentiates between two approaches for identifying HFEs. A top-down approach would start with the analysis of hardware faults and deducing human contributions to those faults, and is widely used in Probabilistic Risk Assessments in the nuclear industry. A bottom-up approach, on the other hand, would look at opportunities for human errors and then model them in terms of potential for affecting safety outcomes. This paper will adopt a bottom-up approach, performing a screening of the interactions between the operators and the system and the subsequent tasks in order to identify the HFEs. The present paper, hence, aims to analyze the interactions between the operators' and the system in the operation of autonomous ships, and identify the possible human failure events that derive from it.

The discussions of this paper are part of an ongoing research aiming to identify and model the risks arising from autonomous ships operation. The scope of this paper is limited to human actions and human failures during operation, under the assumption that the system would work as expected. Therefore, it does not cover system failures, which will be addressed in forthcoming papers by the authors.

Nonetheless, it is important to acknowledge that the possibility of human error is not restricted to the operation of the ships. Human error associated with autonomous ships can be related to design, construction and installation, testing and verification and maintenance, among other activities carried out by humans prior to the operation. This paper does not cover these tasks, as it focuses on the operation only, i.e., it considers that there would be no failures in all of these tasks previous to operation and navigation. Hence, the question it aims to answer is: given perfect design, maintenance, equipment and instruments behavior, could human actions affect safety during autonomous ships operation?

The paper is organized as follows: Section 2 presents the system description and the assumptions made in this study, Section 3 focuses on describing of the interactions between the operators' and the system and the possible Human Failure Events deriving from these interactions. Section 4 presents some concluding thoughts.

2 SYSTEM DESCRIPTION

As stated in Section 1, the ongoing projects on autonomous ships have different concepts in terms of the ship being manned or on the level of autonomy. Utne et al. (2017) use the following definition of autonomy (adjusted from National Institute of Standards and Technology (NIST) (2008)): "a system's or sub-system's own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting, to achieve its goals as assigned by its human operator(s) through designed Human-Machine Interface (HMI)". From fully manual control to fully autonomous systems there can be distinct levels of autonomy (LoA), and the literature provides different proposals for these levels and its taxonomy. One of the oldest taxonomies is the one proposed by Sheridan and Verplank (1978), with 10 LoA, where Level 1 corresponds to fully manual control and level 10 to fully autonomous control. A review of all proposals can be seen in Vagia et al. (2016).

From among the autonomous ship concepts indicated in Section 1, the analysis in this paper is based on the AAWA concept—unmanned ships and dynamic level of autonomy. A dynamic level of autonomy means that the autonomy level can change depending on the context of the voyage, e.g., one phase of the voyage is set to be fully autonomous (Level 10 in the Sheridan and Verplank taxonomy) but the operation encounters a small problem and give the operator a "veto" option before solving it autonomously (Level 6 of autonomy). The reason for choosing this concept are: (i) because it is unmanned, it offers the most different case study from ship operations nowadays, and (ii) because it has a dynamic autonomy level, it covers a different range of situations, from totally autonomous operation to tele-operated control.

Being an unmanned ship, the operators would be working onshore, and we assume they would be working in a Shore Control Center (SCC) as the one proposed in the Munin project. The Munin project website[1] offers a range of information and publications on the Shore Control Center. Essentially, the Shore Control Centre acts as a manned supervisory station for monitoring and remote controlling a fleet of autonomous ships. Most of the time the ships would operate autonomously, without the need for intervention from shore. When needed, though, the operators' in the SCC would provide assistance and may take over control of the ship (Porathe, 2013; Porathe, Prison and Man, 2014; MUNIN, 2016).

The voyage can be divided into four phases, in which the operators would have different possible levels of interaction with the system: Voyage Planning, Unmooring and maneuvering out of dock, Open Sea and Port approaching and docking. The following of these phases is based on the information stated in the AAWA whitepaper (Laurinen, 2016) for a general cargo vessel.

The first phase is the Voyage Planning, in which the operators assess/define certain conditions of the voyage. The operators' assessment makes use of systems that should be present in the ship, such as an automatic system for verifying the sea readiness before starting the voyage. Most of the systems can be checked remotely by the operator while in some areas (such as securing cargo) shore based crew can also be used to check that voyage can be started.

One of the conditions that have to be assessed by the operator previously to the voyage is the connectivity—some of the remote control or remote supervision modes might require a latency and bandwidth that exceeds the capability of the satellite systems in adverse weather conditions. The operator will have then to ensure that there is sufficient connectivity for the intended mission. If there is enough connectivity for the mission, the operator has then to define the primary operational strategy for each leg—autonomous or manual, considering the weather and environmental conditions. Note that manual operation, in this case, means remote operation from the SCC. Next, the operator defines the navigational and fallback strategies. Although the AAWA whitepaper does not describe what the operators take into account during "navigational strategies", we believe that in addition to predefined paths and waypoints it would also include considerations with maintenance (to verify when should the next maintenance of determined equipment be versus the length of the voyage), propulsion and fuel consumption. The fallback strategy, on the other hand, is a strategy executed if the ship experiences an unexpected situation that would require operator intervention. The fallback strategy could include: asking operator to take manual control, slow down and proceed to following waypoint, stop the vessel and stay in DP mode, navigate to previous waypoint, navigate back to preset safe location. The commands and their execution sequence is not same in all parts of the voyage. For example trying to maintain its position in the middle of a congested and narrow fairway in harsh weather might not be a feasible strategy.

It is important to bear in mind that, given dynamic autonomy, the definitions made in the voyage planning are not static, i.e., it can be that one leg was defined to be autonomous but due to external circumstances it goes manual. Moreover, the voyage plan as well as the fallback strategies can always be modified during the voyage using the satellite communication link.

The phase after voyage planning would be unmooring and maneuvering out of dock. The mooring systems can be fully or semi-automatic. A fully automatic mooring system would mean that the operation can be remote controlled or automatically executed by the autonomous vessel. A semi-automatic mooring, on the other hand, means that connection to the quay can be made automatically but the crew is needed to secure the docking. When the ship is maneuvered out of the congested harbor area, it can be controlled by the operator or it can use the dynamic positioning control computer and autonomous control system to reach the waypoint. Moreover, in some areas it could go directly to autonomous mode instead of starting with teleoperation or supervisory control.

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[1] http://www.unmanned-ship.org/munin/

The third voyage phase, after maneuvering out of dock, is the open sea navigation. In autonomous mode the ship executes the voyage according to the defined plan, and the operator receives relevant status data such as ship's location, heading, speed, ETA to next waypoint (or area of closer supervision) and key information from the situational awareness systems as well as critical ship systems.. For situations where the autonomous navigation system's autonomous decision making threshold is exceeded, the operator is notified and can intervene. Therefore, the autonomy level is dynamically adjusted if the mission execution is not proceeding according to the original plan and the autonomous navigation system sees that adjustments are needed. AAWA differs between two different situations: one is a "veto" situation, in which for example the vessel is deviating from the planned course between the two waypoints but stays within specified margins the autonomous navigation system. In this case the system would notify the operator about planned evasion and give the operator a possibility to veto for a limited time. If modifications are needed, the operator can take the vessel in manual control. It can also be that the vessel would need to change the course in such a way that complete waypoint has to be re-planned. In order to ensure that changes to the plan are made in a safe way operator confirmation will be requested. The autonomous navigation system will offer one or more alternatives of how the waypoint could be modified but the operator will finally make the decision how to continue the voyage.

A second case would be a "pan-pan" situation—when there is a complex scenario that the autonomous navigation system path planning and algorithms cannot unambiguously solve. Example of this could be if extremely large number of crafts or other objects are detected and the path planning algorithms are not capable to identify them and thereby the system cannot determine how the navigation should proceed. In this type of scenario the vessel will immediately send a "pan-pan" message to the operator indicating that it is in urgent need of assistance. The ship has a predefined set of fallback strategies (defined at the voyage planning phase) that it will start to execute in the planned order if user response is not received, and depending on the urgency, automatic fallback strategy execution can also be started immediately.

The last phase of the voyage is port approaching and docking. As the other phases, it can be remotely operated or autonomous. This phase together with open sea navigation and unmooring and maneuvering out of dock will be named "navigation phases".

The next section details the interactions between the operators and the system in each of these phases.

3 INTERACTIONS BETWEEN THE OPERATORS AND THE SYSTEM

This section discusses the interactions between operators and the system for each voyage phase of the autonomous ship described in the previous section. It explain the operators' main tasks and the possible decision/action paths they may take when accomplishing these tasks.

The outcomes of the operators' actions will be described in this paper as a "success" or a "failure" of that voyage phase. A successful operation is defined here as an operation that did not encounter any unexpected problem or an operation that did encounter a problem but successfully recovered from it, by operators' actions or autonomous solving. For instance, if during autonomous navigation in the open sea the ship faces a complex situation it cannot solve autonomously and it gives a "pan-pan" alert for the operators, they take over control in time and manage to bring the ship back to a safe status, this is a successful open sea voyage. An unsuccessful operation, on the other hand, is one that encounters a problem and does not recover from it. In the previous example, if the operators fail to respond to the "pan-pan" alert and the ship follows a fallback strategy that is inadequate, this would be a failure in the open sea voyage, leading to an incident.

Note that for voyage planning a failure will not itself cause an accident, but it will increase the probability of having a "veto" or "pan-pan" situations at the following phases. For example, if during voyage planning the operator decides for open sea voyage to be autonomous when the environmental conditions are not safe for the operation, there will be a higher chance that an unexpected situation during the voyage arises and the operator receives a "pan-pan" alert about it. Failures at the following phases, on the other hand, can cause accidents. These may, however, differ in terms of gravity: an accident when still in harbor is less probable to be of catastrophic consequences than during open sea voyage. Yet, the final events treated in this paper will be "success" and "failure", not distinguishing between the severities of this failure, such as collision, grounding, etc. This is illustrated in the general Event Sequence Diagram in Figure 1, where

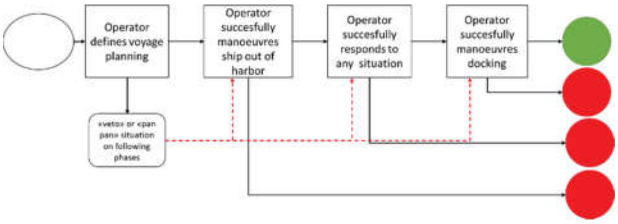


Figure 1. Interaction scheme for voyage planning.

the "success" outcome is represented by the green final event, which is reached if all voyage phases are successful, and the "failures" are represented by the red final events.

For the unmooring and maneuvering out of harbor phase it was considered a fully automatic system, i.e., the operation can be remote controlled or automatically executed by the autonomous vessel, depending on what was defined at the voyage planning phase. Moreover, in spite of the AAWA whitepaper describing the "veto" or "pan-pan" situations only during the open sea voyage, it was considered that they could also happen during unmooring and maneuvering out of harbor and port approaching and docking, when these are in autonomous mode. In this sense, the possible interactions between the operator and the system in the three voyage phases that follows voyage planning are similar: the operation can go manual or autonomous; in case it is autonomous it can i) operate as expected, ii) encounter a small problem and generate a "veto" situation, iii) encounter a more complex problem and generate a "pan-pan" situation. Moreover, the operators' possible responses to these situations are also similar in the three phases. Thus, what will be discussed below for unmooring and maneuvering out of harbor can be extended to the open sea navigation and port approaching and docking.

The operator's interactions with the system in the voyage planning phase are described in sub-section 3.1, and for the following phases, exemplified by unmooring and maneuvering out of harbor operation, in sub-section 3.2.

3.1 *Voyage planning*

From the description in Section 2, it is possible to identify the operator's tasks and possible paths in the voyage planning, which are described in the tables below.

3.2 *Unmooring and maneuvering out of harbor*

The operator's tasks and possible paths in Unmooring and maneuvering out of harbor are described below, and can be extended for the open sea voyage and port approaching and docking phases.

I. Autonomous operation

When the operation is autonomous there can be a small problem that the vessel can solve autonomously, in which case the operator receives a "veto" alert (Table 5). If there is a significant problem, the vessel gives a "pan-pan" alert to the operator (Table 6). In that case, if the operator does not take over control the vessel follows the fallback strategy.

Table 1. Possible operator decisions for Task 1.

Task 1 (T1): Ensure there is sufficient connectivity			
I. If there is no sufficient connectivity, the operator can:		**II.** If there is sufficient connectivity, the operator can:	
T1_path 1: be wrong and believe there is sufficient connectivity, and the operation goes on	**T1_path 2:** be right about the connectivity level and cancel the voyage	**T1_path 3:** be wrong and believe the connectivity is not enough, and cancel the voyage	**T1_path 4:** be right and the operation goes on

Table 2. Possible operator decisions for Task 2.

Task 2 (T2): Define primary strategy for each leg (autonomous or manual)		
T2_path 1: Operator decides that the operation for one leg is autonomous when, due to weather and environmental conditions, it should be manual. For each phase:		
i. Unmooring and maneuvering out of harbor goes autonomous when it should be manual	**ii.** Operation in open sea goes autonomous when it should be manual	**iii.** Port approaching and docking goes autonomous when it should be manual
T2_path 2: Operator decides that one leg should be manual when it could be autonomous		
i. Unmooring and maneuvering out of harbor goes manual when it could be autonomous	**ii.** Operation in open sea goes manual when it could be autonomous	**iii.** Port approaching and docking goes manual when it could be autonomous
T2_path 3: Operator correctly decides that the operation for one leg is autonomous. For each phase:		
i. Unmooring and maneuvering out of harbor goes autonomous	**ii.** Operation in open sea goes autonomous	**iii.** Port approaching and docking goes autonomous
T2_path 4: Operator correctly decides that one leg should be manual:		
i. Unmooring and maneuvering out of harbor goes manual	**ii.** Operation in open sea goes manual	**iii.** Port approaching and docking goes manual

Table 3. Possible operator decisions for Task 3.

Task 3 (T3): Define navigational strategies for the autonomous operations	
T3_path 1: The operator defines an incorrect navigational strategy	**T3_path 2:** The operator decides for a good operational strategy

II. Manual unmooring

To aid in the visualization of these tasks and paths, these interactions are modeled through the schemes presented in Figure 2 for voyage planning and Figure 3 for unmooring and maneuvering out of harbor.

As stated previously, these interactions were modeled not considering system failure yet—e.g. there is a "pan-pan" situation and the alert at the Shore Control Center fails, or the operator takes over manual control and the communication between the SCC and the vessel fails. It isolates, then, the human errors, considering no failure on other aspects of the operation.

From the interaction schemes above it is possible to identify the possible Human Failure Events that could lead or contribute to accidents in autonomous ships operation. Table 8 presents the HFEs involved in the voyage planning phase. Note that these failures would not cause an accident itself, but would contribute for having a "veto" or "pan-pan" situation in the following phases, as illustrated in Figure 1. Table 9 present the HFEs involved in

Table 4. Possible operator decisions for Task 4.

Task 4 (T4): Define fallback strategy for the autonomous operations	
T4_path 1: The operator defines an inadequate fallback strategy	**T4_path 2:** The operator defines an adequate fallback strategy

Table 5. Possible operator decisions for Task 5, after a "veto" alert is received during autonomous operation.

Task 5 (T5): Respond to "veto alert"	
T5_path 1: The operator does no respond to the veto alert	
T5_path 2: The operator responds to the alert and supervise the vessel solve the problem autonomously	
T5_path 2_1: The operator should have "veto" that operation and take over control because the autonomous solutions were not adequate	**T5_path 2_2:** The autonomous solution is adequate
T5_path 3: The operator responds to the alert and take over control of the vessel	
T5_path 3_1: The operator successfully operates the ships	**T5_path 3_2:** The operator fails when operating the ship

Table 6. Possible operator decisions for Task 6, after a "pan-pan" alert is received during autonomous operation.

Task 6 (T6): Respond to "pan-pan" alert	
T6_path 1: The operator does no respond to the "pan-pan" alert	
T6_path 2: The operator responds to the alert and supervise the vessel solve the problem autonomously following the fallback strategy	
T6_path 2_1: The operator should have taken over control of the ship because the fallback strategy is not adequate	**T6_path 2_2:** The fallback strategy is adequate
T6_path 3: The operator responds to the alert and take over control of the vessel	

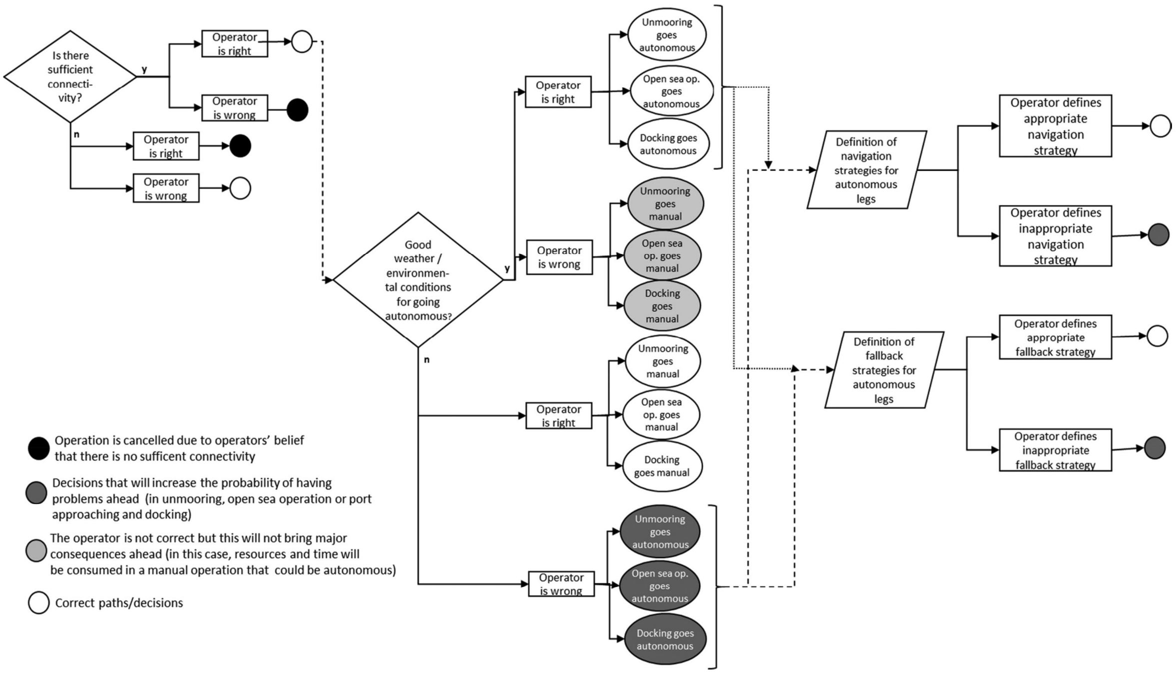
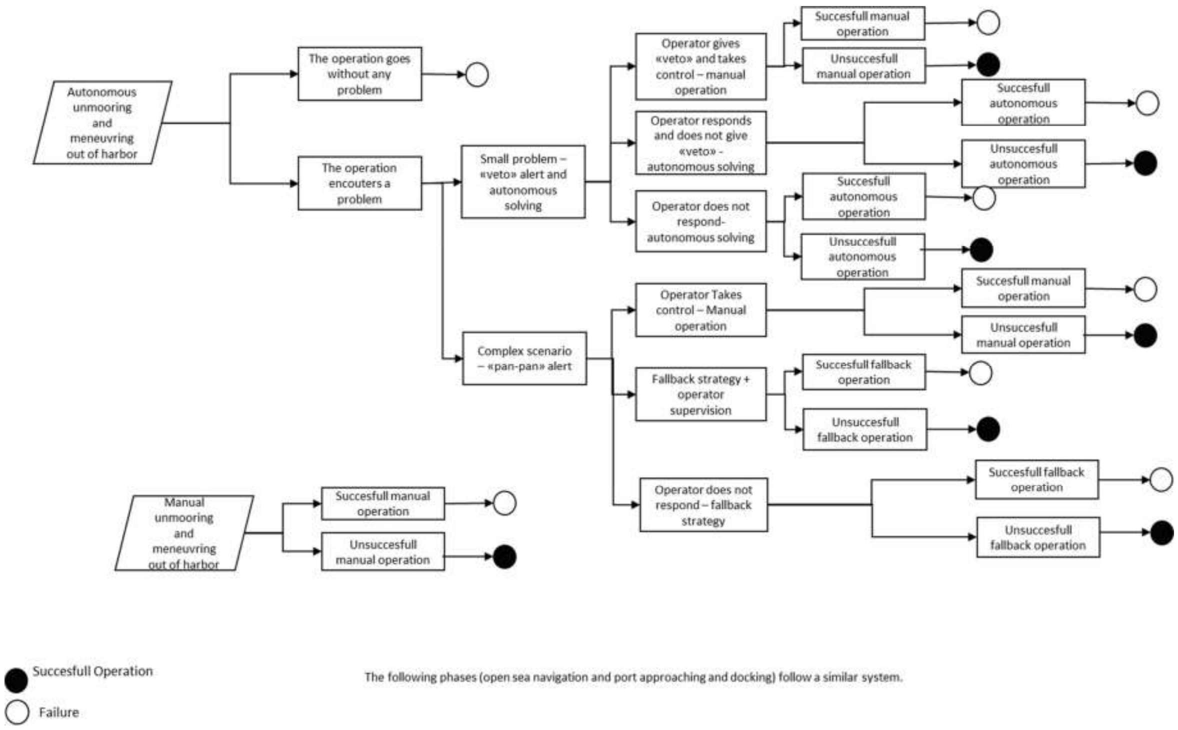


Figure 2. Interaction scheme for voyage planning.



The following phases (open sea navigation and port approaching and docking) follow a similar system.

Figure 3. Interaction scheme for unmooring and maneuvering out of harbour.

Table 7. Possible operator decisions for Task 7, in manual operation.

Task 7 (T7): unmooring and maneuvering out of harbor by tele-operation	
T7_path 1: Operator successfully operates the ship	**T7_path 2:** Operator fails to operate the ship

the following phases (navigation phases). These are the HFEs that could lead to the "failure" final events in Figure 1.

The Human Failure Events presented in Table 8 and 9 are defined rather broadly, and can be decomposed, if needed, to identify sub-HFEs. In this sense, they are a general representation of what could go wrong, in terms of human failure, in the autonomous ships operation. They are a starting point that allows to analyze, for each HFE, the crew cognitive processes involved, in order to identify more specific Failure Modes that would lead to each HFE. Furthermore, for each Failure Mode it will be possible to identify and assess the factors that influence the operator's decisions and actions—the Performance Influencing Factors (PIFs).

In this sense, as stated in Section 1, the identification of Human Failure Events is the first step towards a solid Human Reliability Analysis.

The description of the operator-system interactions in autonomous ships and possible HFEs

Table 8. Human failure events in voyage planning phase.

Path	Human Failure Event	Description
T1 path 1	Failure to correctly assess connectivity level	The operator is wrong about the low level of connectivity. The operation goes on, and the low level of connectivity can lead to communication problems between the SCC and the ship.
T2 path 1	Failure to correctly define primary strategy	During definition of the primary strategy for each leg the operator believes the conditions are adequate for autonomous operation when, in that situation, it should be manual (tele-operated)
T3 path 1	Failure to define adequate navigational strategy	The operator defines an inadequate navigation strategy. This will increase the probability of having problems ahead and a "veto" or "pan-pan" situation
T4 path 1	Failure to define adequate fallback strategy	The operator defines an inadequate fallback strategy. In case there is a "pan-pan" situation the fallback strategy will be followed by the ship, if the operator does not take manual control of the ship

Table 9. Human failure events in navigation phases.

Path	Human Failure Event	Description
T5_path 1 **T6_path 1**	Failure to respond to an alert	The operator does no respond to an alert, which may be a "veto" alert or a "pan-pan" alert.
T5_path 3_2 **T6_path 3_2** **T7_path 2**	Failure to remote-operate the ship	The operator is manually operating the ship, which may be after a "veto" or a "pan-pan" alert or may be from the beginning of that operation, in case it was defined to be manual.
T5_path 2_1 **T6_path 2_1**	Failure to take over control of the ship when necessary	The operator trusts the autonomous solution or fallback strategy and does not take over control of the ship in a situation where this is needed

deriving from it demonstrates that there is still room for human failure in its operation. The assessment of human error, therefore, cannot be neglected or minimized when considering autonomous ships' safety and reliability.

4 CONCLUDING THOUGHTS

This paper demonstrates that although compared to conventional ships the human interaction is reduced in autonomous ships, the human still plays a role, with a potential for human error that has to be considered.

One of the concerns regarding autonomous ships' operation is the new risks they can pose, and how to asses them. Being a novel operation, the possible interactions between operator and autonomous ships are not yet clear, but this paper contributes to identifying these interactions and modeling it. The paper also identifies, at a high level, possible Human Failure Events deriving from these interactions.

Three HFEs deserve particular attention, for they can lead/contribute to an accident such as collision, grounding: a failure to respond to an alert, a failure to remotely operate the ship, and a failure to take over control of the ship when necessary. A deeper analysis of these events is needed to identify possible failure modes and the factors that can influence them. That analysis, in the context of an HRA, will make it possible to identify opportunities to reduce the likelihood of critical human failures.

Moreover, it can be a basis for discussing whether autonomy will indeed reduce the likelihood of accidents caused/aggravated by human error—and to determine the appropriate level of autonomy that can lead to a safer operation.

It is important to point that this paper approaches human actions focusing on their contribution to accidents. Actions of operators onboard, however, contribute also to avoiding accidents and/or to reducing the severity of their consequences. This aspect needs to be evaluated as well in further discussions on the shift from onboard to onshore operation.

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