Advances in Reliability, Safety and Security, Part 1 – Kołowrocki, Dąbrowska (eds.)

Advances in Reliability, Safety and Security

ESREL 2024
Monograph Book Series

System Theoretic Process Analysis Based Safety On Different Autonomy Levels Of Autonomous Ships For Short Sea Service

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Abstract

Ensuring safety and reliability constitutes one of the primary concerns associated with the approval of autonomous ships. Currently, multiple risk-based studies on autonomous ships are ongoing but still lack adequate safety assurance to get approval. This paper presents a comparative risk analysis that specifically focuses on identifying hazardous scenarios related to operating in or switching to different system control modes during different phases of autonomous operation. The objective is to gain insight into how the choice of control mode corresponding to different autonomy levels affects safety in different phases of the operation and under various circumstances. The analysis is based on a use case autonomous ship under the SEAMLESS project that operates from Bergen to Ågotnes and vice versa. The system theoretic process analysis (STPA) method is applied to identify the unsafe control actions (UCA)s and related hazardous scenarios during unmooring, unberthing, and port departure phases. Initially, a concept of operations (CONOPS) is formulated for the use case vessel to describe the functional design conditions and scenarios. The application of STPA and the categorization of safe modes of operations will help to improve the CONOPS in further studies. This paper aims to analyze hazards associated with the operational phases mentioned earlier across various potential control modes of the ship. It compares UCAs and loss scenarios to ascertain whether certain control modes are safer or more hazardous than others during different operational phases. Finally, based on these findings, the paper proposes recommendations. The research presented in this paper will help to enable the safe and reliable operation of autonomous ships for short sea service (SSS) and lead to its approval.

Keywords: maritime autonomous surface ships (MASS), operational modes or autonomy levels, safety, hazards, STPA, unsafe control actions, short sea service

1. Introduction

Maritime autonomous surface ships (MASS) have brought about significant advancements in the maritime industry. It holds the potential to reduce the number of accidents (i.e. increase the safety of maritime operations and shipping), increase the financial benefits, and save time (Burmeister et al., 2014; Heij and Knapp, 2018). Different definitions have been proposed for MASS. Based on an extensive review of clusters generated by bibliometric tools, Jovanović et al., (2024) proposed the following definition: “An autonomous ship is a vessel that is capable of operating and navigating without direct human intervention. It relies on various technologies such as artificial intelligence, robotics, sensors, and advanced control systems to perform its functions autonomously. An autonomous ship can make decisions, adapt to changing conditions, and perform tasks without constant human input or control”. To enable autonomous operations, an autonomous or remotely controlled ship must be equipped with robotics or automation technologies for various mechanical and control equipment. This equips the ship to make autonomous judgments and decisions when confronted with unexpected internal or external situations, facilitated by its autonomous and remote-control system (Im et al., 2018).

The level of autonomy is an important factor in determining the extent of autonomous decision-making. Various taxonomies have been introduced to characterize the degree of autonomy in systems, depending on the allocation of tasks between humans and the system (Camila Correa-Jullian, 2023). This present study has adopted the classification by Rødseth et al., (2022) presented in Table 1.

Table 1. Definitions of autonomy levels proposed in (Rødseth et al., 2022).

Representation	Autonomy level	Explanation
FA	Fully autonomous	No operator is in the control position, and automation can handle all expected events in this state.
AC	Autonomous control	The operator is away from the control position for a known period and can, when necessary be alerted by the automation with sufficient time to get back.
OA	Operator assisted	The operator is always near the control position. The operator can leave the control position for shorter periods but needs to exercise their own judgment as to how long he or she can be away.
OE	Operator exclusive	The operator must be always in the control position.

Many studies on MASS operations are either conceptual or at the early design stage. The motivation for all the studies (Andreas Lien Wennersberg et al., 2020; Pietrzykowski and Hajduk, 2019; Rødseth et al., 2022) are indirectly the same, that is to present the concept of new technological operations and functional design of different autonomy levels in different conceptual ways. A common framework can help to develop a general description of the control structure and technological operations for different levels of autonomous ships (Chaal et al., 2020) and they constitute a framework of three parts to present the functional description of the autonomous ship.

Ensuring safety and reliability constitutes one of the primary concerns associated with the approval of autonomous ships. One of the criteria for an autonomous vessel is to be as safe as or safer than the most advanced manned ships (Rødseth and Burmeister, 2015). To achieve this, rigorous and systematic risk and safety analysis is required. Different regulatory organizations have guided the installation as well as operation procedures of MASS. All of them have pointed specifically toward safety assurance of it. The Norwegian Maritime Authority or NMA has published one such set of guidelines (NMA, 2022). The first point in these guidelines is to conduct a HAZID analysis to ensure an equal safety level as the current conventional manned vessels. The recent interim guidelines of IMO for MASS trials emphasize the significance of safety, security, and environmental protection (IMO, 2023). It also signifies the need for qualified personnel and robust cyber risk management. In addition, according to the ClassNK guidelines, it is necessary to confirm the safety of the design of the autonomous system by using an appropriate risk analysis method (NK Guidelines, 2020).

A particular challenge with autonomous ships is that a variety of potential hazards can appear, as a consequence of operating at different autonomy levels (Ventikos et al., 2020). Recently, several risk-based investigations focusing on various aspects of automation and operations in autonomous ships have been conducted. These studies aim to identify risk factors associated with both automation and operational elements. The majority of studies are associated with collision avoidance (COLREGs) (Chun et al., 2021), (Wang et al., 2023), (Bolbot et al., 2022) and navigation system (Perera, 2019), (T. Kim et al., 2022), (Ha et al., 2021). Namgung and Kim, (2021) present a collision risk inference system for MASS that complies with COLREGs vital rules for collision avoidance. Felski and Zwolak (2020) discuss the operational threats and challenges of ocean-going autonomous ships and find more complexity with the network of navigational data. Yamada et al., (2022) focus on the autonomous ship conceptual design and identify that information transfer needs to be improved, in addition to audio-visually noticeable alarms, and - alarm function to communication abnormality between the MASS and ROC. Many other studies also present the same challenges of navigational as well as operational (Ha et al., 2021), (Fastvold, 2018), (Burmeister et al., 2014). Another crucial challenge is object identification reliability during autonomous navigation that allows the system to find out and respond to conditional stimuli (Shao et al., 2022). A framework is proposed in (Fan et al., 2020) where the factors influencing the navigational risks of remotely controlled MASS are identified, the study assessed four operational phases that include voyage planning, berthing and unberthing, port approaching and departing, and open sea navigation. It also defines several factors related to humans, ships, environments, and technology based on an extensive literature review and expert knowledge.

Furthermore, there are several other studies on autonomous ships with a view to ensuring safety by different hazard analysis methods such as STPA, HAZID (hazard identification), FMEA (failure mode effect and analysis), and more. Wróbel et al., (2018) used STPA to identify 24 high-level components of MASS that are affected after analyzing a total of 46 control actions. Chang et al., (2021) performed an overall risk assessment of MASS based on the FMEA method and Bayesian network. The analysis by (Hoem et al., 2019) identifies the particular risks associated with the different levels of autonomy compared to the contemporary conventional, manned ships. They have remarked that increasing the autonomy levels comes with increasing technical risks (such as sensor failure, loss of steering, software error, etc) whereas lower levels of autonomy can have an increasing number of mix of risks related to Human Machine Interfaces (HMI) and loss of the capability of crews. The risks include ship-to-ship collision (Abilio Ramos et al., 2019), the risk of ship grounding (Hänninen et al., 2014), and the risk of fire on board (Cicek and Celik, 2013). To formulate an early safety management strategy with safety controls, the study in (Valdez Banda et al., 2019) adopted the STPA hazard analysis method.

They aimed to develop a pre-concept design phase for autonomous ferries that includes the Concept of Operations (CONOPS). STPA is an effective way to integrate safety in complex systems (Chaal, Valdez Banda, Glomsrud, et al., 2020), thus the study formulates a framework that models the STPA hierarchical control structure for autonomous ships. A hierarchical control structure based on STPA is also adopted by (Rokseth et al., 2019) to determine the autonomous ship system requirements and verification. The control structure is based on four systems: the automatic sailing system, the autopilot, the motion control system, and the power system. Besides, Chaal et al., (2020) studied on technological developments of MASS and suggested improvement in six research fields that cover most of the technological shortcomings. Rødseth and Burmeister, (2015) assessed MASS with the IMO’s Formal Safety Assessment elements and formulated a risk-based framework to identify if autonomous or unmanned ships can attain the same safety level as conventional ships. The assessment indicates that following some specific safety measures the safety level is achievable. However, Rødseth et al., (2023) conclude that the best possible and effective short-term solution is to cooperate the autonomous ships with human operators. The best longer-term solution may be to improve the information exchange between the ships, complemented with changes in COLREGs.

Ventikos et al. (2020) explain the hazards for the system as a function of the vessel’s autonomy level with the help of the system theoretic process analysis (STPA) method. Furthermore, H. Kim et al. (2019) identify and compare scenarios that may lead to hazards based on six autonomy types. In this study, we systematically identify how and why inappropriate actions such as selecting an unsuitable course or speed, may emerge in an autonomous ship, potentially causing a hazard to itself and other vessels. This process is conducted using the System Theoretic Process Analysis (STPA) method. The paper aims to analyze how unsafe control may arise from the remote operating center and the autonomous onboard controller during a set of operational phases (as illustrated in Figure 1) of the vessel. We will focus specifically on identifying hazardous scenarios related to operating in or switching to, different system control modes or autonomy levels during different phases of autonomous operation. The objective is to gain insight into how the choice of control mode corresponding to different autonomy levels affects safety in different operation phases and under various circumstances. The analysis is based on a use case of an autonomous ship under the SEAMLESS project that is planning to operate from Bergen to Ågotnes and vice versa (SEAMLESS, 2023). Initially, a concept of operations (CONOPS) is formulated for the case study vessel to describe the functional design conditions and scenarios. The research presented in this paper will contribute towards enabling the safe and reliable operation of autonomous ships for short sea service (SSS), which is an important step towards the approval of autonomous ships.
The study is organized as follows: Section 2 presents the methodology where the procedure of the STPA method along with its significance is explained and a Concept of Operations (CONOPS) is formulated to describe the use case of the SEAMLESS project while section 3 demonstrates the analysis and results. Sections 4 and 5 represent the discussion and conclusion including the future research respectively.

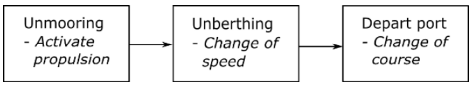


Fig. 1. Operational phases along with the control actions.

2. Methodology

System Theoretic Process Analysis (STPA) is a hazard analysis method based on Systems-Theoretic Accident Modeling and Processes (STAMP) which is an accident model focusing on potential causes of accidents beyond component failures (Leveson, 2016). In addition, to component failures, accidents can be caused by design errors, component interactions, and other social and organizational factors. STPA is furthermore suited for studying the safety of a system even with limited information and empirical data (Leveson, 2016). The method is based on a hierarchical control structure of the system where the relationship and interactions between control entities (such as human and electronic controllers) and controlled processes are modelled through control actions and feedback signals. The basic assumption in STAMP (and STPA) is that accidents are caused by inadequate and unsafe control and the objective of STPA is to identify how unsafe control actions in the hierarchical control structure may occur, and how they can be prevented (Leveson and Thomas, 2018).

When conducting hazard analysis for autonomous ships, it is crucial to shift focus from solely examining equipment failures to also considering both software and human factors (Yamada et al., 2022). As STPA is a method that analyses large-scale and complicated systems, it is highly applicable to MASS. STPA uses a functional model of the system, hence the study (Ventikos et al., 2020) finds STPA more effective than other hazard analysis methods, such as fault tree analysis (FTA), failure modes and effects criticality analysis (FMECA), and hazard and operability analysis (HAZOP) in identifying potential hazards of different autonomy

levels. A total of 29 hazard analysis methods are investigated for autonomous ships in (Zhou et al., 2020). System safety requirements and evaluation criteria based on the characteristics of autonomous ships are established using a system engineering approach. After a comprehensive review of an extensive number of hazard analysis methods, the study suggests that STPA is the best approach for the hazard analysis of autonomous ships. Based on safety engineering, Karanikas, (2016) analyse accidents by making a review of the socio-technical system with the help of STPA and provides a systematic way to model accidents and safety. This analysis with the STPA is more effective as it also presents the process of accident occurrence as well as preventive measures in a less subjective but better understanding way (Fleming et al., 2013).
A detailed description of all four steps is published in the handbook (Leveson and Thomas, 2018). The key description can be presented as follows:

- *step 1*: In this step, the purpose of the analysis is defined by determining the system-level accidents, hazards, and safety constraints;
- *step 2*: This step aims to capture functional relationships and interactions by modelling the system as an interconnected set of feedback control loops;
- *step 3*: In this step, potential unsafe control actions that may cause the system-level hazards are identified. Leverson and Thomas, (2018) define an unsafe control action as "control action that, in a particular context and worst case-environment, will lead to a hazard";
- *step 4*: The purpose of this step is to determine why the unsafe control actions may occur by identifying loss scenarios.

2.1 Case study

The case study is related to the SEAMLESS project (SEAMLESS, 2023) which will investigate the application of a transport system like that of ASKO, as described in (Hagaseth et al., 2023), where a dedicated liner service for transporting containers between two ports is operated by an autonomous ship.

The background for the case study is that the container terminal in the Bergen city centre will be moved to a rural location in the main fairway. One of the alternatives under investigation is to move it to Ågotnes. The motivation for the relocation is to reduce truck traffic in the city centre, but other advantages are that larger container ships can reduce their sailing distance and do not need to navigate into the rather small and busy port area. The idea is that the container vessels can deliver and load all containers going into or out of the region at one terminal located in the main fairway. Smaller shuttles will then distribute and consolidate the containers by operating between ports and smaller quays in the region. A small container terminal will remain in the Bergen city centre, for cargo going to and from the city. SEAMLESS therefore investigates the viability of an autonomous feeder loop network, and part of this is a dedicated liner service between Ågotnes and Bergen. The liner service between Ågotnes and Bergen is the case study for this research.

2.2 CONOPS

To perform the STPA, certain elements of the CONOPS are needed. These are the system description and the operational phases. As our use case is the application of the same system as in (Hagaseth et al., 2023), for a different operational area, we base the STPA on the CONOPS given therein.

As the use case vessel is the ASKO Maritime autonomous vessel, the ship particulars are the same as in (Hagaseth et al., 2022). The route between Bergen and Ågotnes has a sailing distance of 11nm.

Fig. 2. Operational route of the use case A.(SEAMLESS, 2023).

2.3 System illustration

This section presents the operational overview of the vessel with a simplified illustration for a better explanation. The illustration is related to the ship-to-ship and shore-to-ship communications as well as interference.

2.4 System description

Ship control and operational tasks are shared between an autonomous onboard controller (AOC) and human operators at the remote control center (ROC). The definition, functions, and challenges of the ROC are detailed in (Dybvik et al., 2020). The onboard systems (main engine, auxiliary engines, power management system, etc.) receive the starting command from the ROC and are also acknowledged to the AOC. After system activation, the goal is for the AOC to take the lead in executing the operation, while the ROC monitors the proceedings. However, control can be shifted and shared between ROC and AOC during the entire operation based on the context and autonomy levels or operational modes. If a situation arises that the AOC cannot handle, it should instantly notify the ROC which should take over the control within a specified time so that any unexpected situation can be controlled. Individual responsibilities of the ROC and the AOC are specified more in detail in (Hagaseth et al., 2022). In general, both the AOC and the ROC can be active performing different actions at the same time during the same operational phase. Different operational modes have functional tasks in different ways based on the ROC and AOC involvement during the operation. When the vessel is activated and ready to start its mission, the next step is unmooring, followed by unberthing, and departing from the port. Once the port has departed, the vessel follows the designated route defined in the voyage plan provided by the ROC. From Figure 3 it is seen that the vessel motion is maintained with continuous communication between ROC and AOC with the help of satellite or maritime broadband radio (MBR). Any notification from the vessel traffic service (VTS) or, other vessels, is communicated directly to the ROC and then forwarded to the AOC by the ROC if relevant. Therefore, two major controllers are there to execute three control actions. The three control actions are "Activate Propulsion, Change of Speed, and Change of Course".

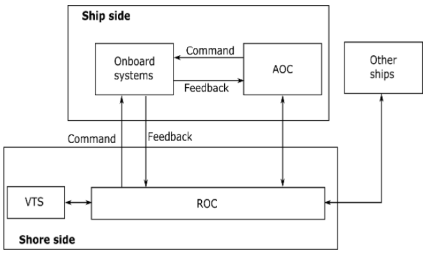


Fig. 3. System illustration of MASS operation for SSS. Inspired from (Hagaseth et al., 2022).

3. Result

In this section, the STPA method is applied to identify the UCAs from four specified autonomy levels. The UCAs are illustrated and presented within figures and tables and then structured.

3.1 STPA: step 1

In this study, the system boundary is associated with the autonomous ship operation for short sea service. Four different autonomy levels are analyzed for three specific operational phases which are unmooring, unberthing, and departing port. At first major possible losses are identified and marked with the letter "L". After that, system-level hazards and system-level constraints are presented in Table 2. System-level hazards lead to losses whereas system-level constraints (SC) prevent those losses. Losses are as follows:

- *L-1*: Loss of life or injury to people (another manned vessel/s);
- *L-2*: Delayed arrival;
- *L-3*: Loss of property;
- *L-4*: Loss of cargo;
- *L-5*: Environmental pollution.

Table 2. System-level hazards and system-level constraints.

System level hazards	System level constraints
H1) The ship collides with or is collided by another ship/s or object/s. (L1, L2, L3, L4, L5)	SC1) The ship must not collide with another ship/s or objects/s.
H2) The ship loses its position or intact stability. (L2, L3, L4)	SC2) The ship should not lose its position or intact stability.
H3) The ship produces inappropriate propulsion power. (L1, L2, L3, L4)	SC3) The ship must produce appropriate propulsion power.
H4) The ship fails to maintain its planned route. (L1, L2, L3, L4, L5)	SC4) The ship should maintain its planned route.
H5) The ship does not maintain the planned speed on the crossing. (L2, L3, L4)	SC5) The ship must maintain the planned speed on the crossing.

3.2 Model the control structure

The functional control structures for all four autonomy levels are illustrated in this section. This control structure is mainly a flow of control commands, and feedback which are identified with their specified arrow markings. The HO is the main controller from the shore while AOC is the main controller from the ship side.

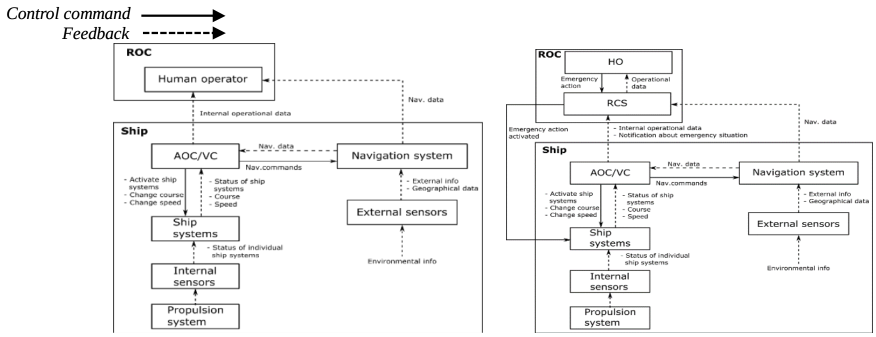


Fig. 4. (a) Control structure of fully autonomous; (b) Control structure of autonomous control.

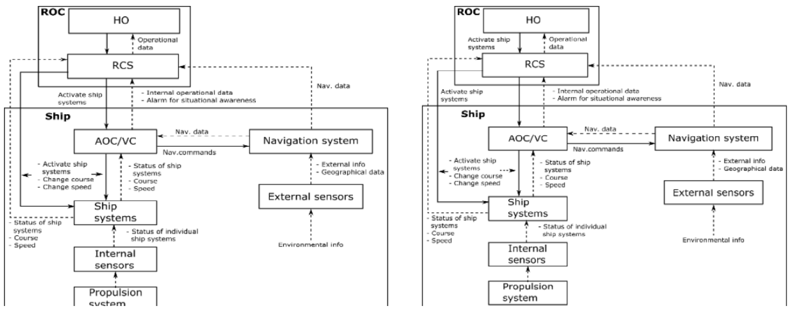


Fig. 5. (a) Control structure of operator assisted; (b) Control structure of operator exclusive.

3.3 Step 3: Identifying Unsafe Control Actions (UCAs):

In this step, possible UCAs provided by the HO and AOC are determined by analysing three specific control actions (each of which can be provided by either controller) within four modes of operation (corresponding to four autonomy levels). UCAs are identified based on the structure of a table, such as Table 3, and by identifying various conditions where providing, not providing, etc. is hazardous.

Table 3. Identification of UCAs from AOC within the "Fully Autonomous" autonomy level during the unberthing phase of operation.

Controller: AOC									
ID	Control action	Condition		Unsafe control actions					
		Change of speed is required	Change of speed is feasible	Not provided	Provided	Too early	Too late	Too short	Too long
CA.AOC.037	Change of speed	Yes	Yes	Unsafe(H1,H5)	Safe	Unsafe(H5)	Unsafe(H1,H5)	N/A	N/A
CA.AOC.038		Yes	No	Unsafe(H1,H5)	Unsafe(H1)	Unsafe(H1)	Unsafe(H1,H5)	N/A	N/A
CA.AOC.039		No	Yes	Safe	Unsafe(H5)	Unsafe(H1)	N/A	N/A	N/A
CA.AOC.040		No	No	Safe	Unsafe(H1,H5)	Unsafe(H1,H5)	N/A	N/A	N/A

In total 24 Tables similar to Table 3 were constructed to cover all three control actions for both controllers and during each of the four modes of operation. Tables 4, 5, and 6 summarize the number of identified UCAs for each case.

The total number of identified UCAs by each controller for all three control actions and all four operational modes during the three phases are presented in Table 7 and Figure 6 (a). Figure 6 (b) illustrates the percentage difference between the two controllers.

Table 4. Number of UCAs while executing the control action "Activate Propulsion" during the "Unmooring" phase operation.

Autonomy level	Operator		Total
	HO	AOC	
Fully autonomous	0	7	7
Autonomous control	2	7	9
Operator assisted	7	2	9
Operator exclusive	7	0	7
Total	16	16	32

Table 5. Number of UCAs while executing the control action "Change of Speed" during the "Unberthing" phase operation.

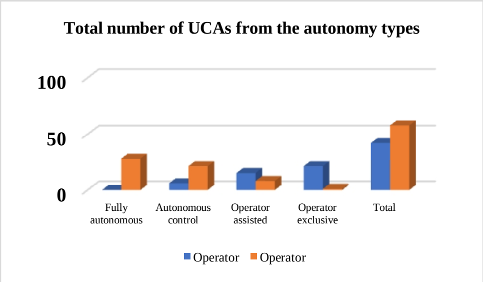
Autonomy level	Operator		Total
	HO	AOC	
Fully autonomous	0	11	11
Autonomous control	2	7	9
Operator assisted	3	3	6
Operator exclusive	7	0	7
Total	12	21	33

Table 6. Number of UCAs while executing the control action "Change of Course" during the "Depart Port" phase operation.

Autonomy level	Operator		Total
	HO	AOC	
Fully autonomous	0	10	10
Autonomous control	2	7	9
Operator assisted	5	3	8
Operator exclusive	7	1	8
Total	14	21	35

Table 7. Total number of UCAs during all three phases.

Autonomy level	Operator		Total
	HO	AOC	
Fully autonomous	0	28	28
Autonomous control	6	21	27
Operator assisted	15	8	23
Operator exclusive	21	1	22
Total	42	58	100



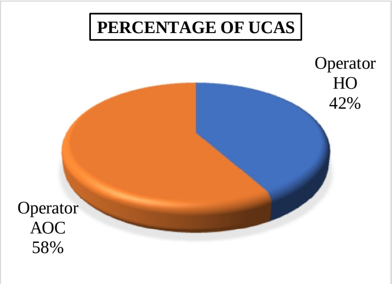


Fig. 6 (a) Total no of UCAs from four autonomy types; (b) Percentage of UCAs from HO and AOC.

Table 8. Examples of loss scenarios.

Autonomy type	Reasons	UCAs	Loss Scenarios
Fully autonomous	Power failure	*UCA.AOC.070.004:* The vessel needs to change the course to avoid a collision, etc but the AOC provides the required course change command too late, and the course change is not feasible. (H1)	*LS.AOC.070.004*: The provided course angle is not feasible due to an internal power failure. The AOC receives the command too late and may lose its position or stability and collide with another object.
Autonomous control	Flawed algorithm	*UCA.AOC.069.001:* The vessel needs to change the course to avoid collision, etc and the course change is feasible, but the AOC does not provide the required course change command. (H1, H2, H4)	*LS.AOC.069.001:* The AOC does not provide the required course change command because of a flawed algorithm in the control loop.
Operator assisted	Sensor failure	*UCA.HO.050.001:* A speed change is required to maintain the voyage plan, avoid a collision, etc, and the HO provides the speed change command, but the change of speed is not feasible. (H1)	*LS.HO.050.001*: The HO is not aware that the given speed change is infeasible due to the failure of an external sensor. As a result, the vessel may collide with a nearby object such as a ship.
Operator exclusive	Wrong interpretation of the feedback.	*UCA.HO.057.001:* A speed change is required to maintain the voyage plan, avoid a collision, etc and the speed change is feasible. Still, HO does not provide the required speed change command. (H1, H5)	*LS.HO.057.001:* The HO does not provide the required speed change command because the HO incorrectly interprets the speed change signal and does not take the correct step on time.

3.4 Step 4: loss scenarios

Loss scenarios are scenarios leading to the UCAs. Generic reasons for UCAs can be equipment failures such as power failure, algorithm flaws, incorrect interpretation of a command by an actuator or another controller, incorrect interpretation of a feedback signal by a controller, time lag in a feedback signal or a command signal, missing feedback, disturbances from other processes, and more. For a detailed overview see Leverson and Thomas, (2018). Some examples of loss scenarios leading to UCAs from each operator mode or autonomy type with individual codes are listed in Table 8**.**

4. Discussion

The study was conducted to identify and understand how inadequate control of an autonomous ship may occur during different operational phases and operational modes. In Figures 4 (a), 4 (b), 5 (a), and 5 (b)**,** the control structure is formulated for the operation of four autonomy types. HO and AOC create different types of UCAs within those individual autonomous operations. From Table 4 we observe that during the Unmooring phase operation, both fully autonomous and operator-exclusive modes yielded the same number of UCAs, which was also the lowest compared to the other two modes. Next, from Tables 5 and 6**,** during the Unberthing and Depart port phases, a fully autonomous operation where AOC is the only controller, creates the greatest number of UCAs. Conversely, operator-assisted, with both HO and AOC controllers, resulted in the lowest number of UCAs. It is also interesting to note that during the operations, AOC is the only controller for the fully autonomous type and HO is the only controller for operator exclusive type except during depart port when AOC has very limited control and may create only one UCA. Note from Table 7 and Figure 6 (b), that AOC can create more UCAs than the HO for the specified operations. In the case of autonomy types, fully autonomous produces more UCAs than the other three types whereas the lowest UCAs are expected from operator exclusive type. Furthermore, during the unmooring phase, UCAs are more likely to create hazard “H3” and during unberthing and depart port phases UCAs lead to hazards “H1, H5” and “H1, H2, H4” respectively. H1 is more critical as it is involved with collision and leads to serious accidents. Therefore, “change of speed and change course” actions during the unberthing and depart port phases respectively are more sensitive than the “activate propulsion” action of the unmooring phase. Further, the “change of course” action seems the most sensitive because it evolves the maximum number of UCAs, and the effect as well as the number of hazards from these UCAs is max. Hence, if we make a priority of the operating phases from more sensitive to less sensitive, it can be as follows:

1) Depart port (Change of course) (35);
2) Unberthing (Change of speed) (33);
3) Unmooring (Activate propulsion) (32);

Moreover, Figure 6 (b) illustrates that more UCAs arise from AOC that need more focus to maintain enough safety constraints with regular maintenance such as check-ups at the interval of the voyage, proper system installation, regular updates, etc. HO also needs to have proper training about the rules and responsibilities of the ROC because a lack of experience with the new technologies can cause challenges (Wennersberg et al., 2020). However, this study aims to focus mainly on identifying safer autonomy types. If we rank safer autonomy types based on the number of UCAs, the following order appears (from safer to more unsafe),

1) Operator-exclusive (22)
2) Operator-assisted (23)
3) Autonomous control (27)
4) Fully autonomous (28).

From the ranking, fully autonomous is the most sensitive mode because of its maximum number of UCAs especially during the change of speed and course actions. Ranking the safer mode of autonomy based on the number of UCAs may not be effective always because the consequences of hazards derived from the individual UCA are not the same always. For example, the withering effect between the hazard “H1” and “H2” is not the same. In addition, certain UCAs may occur frequently but produce fewer hazards while some UCAs with less frequency create more hazardous impacts. In this analysis, during each phase of operation, both controllers possess the same types of hazards from individual UCA. Hence, the ranking is more relevant and effective. It seems from the ranking that operator-exclusive and operator-assisted are very close in safety aspects, they can be switched depending on the context during the operation. As our operational analysis has three specific phases, autonomy types or operator modes can be selected separately during each phase or control action of operation. For example, during the unberthing phase and speed change control action, operator-assisted creates the lowest number of hazards, it can be selected for that phase and control action.

However, the number of UCAs may not necessarily be a strong indicator of which mode is the safest. The reason is that every UCA may not have the same impact, or the consequences of every hazard may not be the same. So, even if the number of operating modes can carry more UCAs than others, but still may be safer and vice versa. In addition, during the unberthing and depart port phases both "change of speed and change of course" actions may need to be executed simultaneously.

5. Conclusion

This paper discusses the STPA application on autonomous vessels' autonomy types or operator modes for short sea service to identify the safer type of autonomy for three specific operating phases. During all operational phases, HO and AOC are the controllers from the shore side and ship side respectively, and create different types of unsafe control actions.

The main observation from this analysis is that AOC alone during fully autonomous operation may give rise to more unsafe control actions than any other mode of operation. HO alone as a controller during the operator-exclusive type creates less unsafe control actions. Another observation is that during an individual phase of operation, safer operator modes can be different. Hence, based on the operating condition and phase, the operator mode can be selected and switched for safer operation. The last observation is that during the unberthing phase and Change of Speed control action, the combination of HO and AOC results in the fewest number of UCAs. That means the combination of humans and AI is also significant.

Depth analysis with real implementation is required on the evolved UCAs for their validation and effect to ensure an effective, safer priority mode of operation. In addition, future work should also be on identifying the possible hazards during shifting from one mode of operation to another mode. Moreover, further research is also needed on the human-machine interaction and control actions, and autonomy types during open sea, and arrival operations.

Acknowledgements

Funded by the European Union, Grant Agreement N° 101096923. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

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