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Safety Analysis of Human Machine Interactions in Remotely Operated Maritime Autonomous Surface Ships

Muhammad Irsyad Hasbullah,

Naval Architecture, Ocean & Marine Engineering, University of Strathclyde, Glasgow, United Kingdom. E-mail: irsyad.hasbullah@strath.ac.uk

G Theotokatos

Naval Architecture, Ocean & Marine Engineering, University of Strathclyde, Glasgow, United Kingdom. E-mail: irsyad.hasbullah@strath.ac.uk

Commercial deployment of Maritime Autonomous Surface Ships (MASS) is on the verge of becoming reality. Remote control centres (RCC) are developed, which however involve human operators to monitor and control MASS operations. Human-Machine Interactions (HMI) impact the MASS safety and robust decision-making, whereas technologies advancement along with emergencies, such as connectivity loss, human errors, and algorithm failures, cause additional. The study aims at developing systematic method for HMI mapping and appraisal combining the Systematic Theory Process Analysis (STPA) with Model-Based System Engineering (MBSE), targeting to minimise human error and risks in remote operations. A reference system that consists of human operators, interfaces, autonomous sub-systems and navigation system is analysed considering the case study of a remotely controlled vessel supervised by the RCC operator. The results reveal potential safety issues due to faults or errors and their causes. For instance, human error caused by distraction and inadequate training lead to ineffective decision making. This study establishes the foundation for developing human-informed design solutions, and robust remote operating systems for future RCC for autonomous ships, ensuring seamless and efficient interactions between humans and machines.

Keywords: Maritime autonomous surface ships, remote control centre, human machine interactions, safety analysis, Systematic Theory Process Analysis, Model-Based System Engineering.

1. Introduction

The development of Maritime Autonomous Surface Ships (MASS) represents a significant transformation in the maritime industry, driven by advancements in automation, artificial intelligence (AI), and remote-control technologies. MASS promises benefits such as reduced operational costs, enhanced sustainability, and improved safety. By minimizing human presence onboard and integrating advanced navigation and collision-avoidance systems, autonomous ships aim to outperform traditional safety standards (Tsvetkova and Hellström 2022). However, these advantages also introduce new challenges, particularly in the realm of human-machine interactions (HMI), where human operators must oversee and intervene in remote operations when necessary.

The transition to remotely operated MASS presents unique risks in human-machine collaboration, especially in complex systems where multiple entities interact. These entities, including the remote-control centre, satellite connectivity, and port facilities, form a highly interconnected ecosystem (as shown in Figure 1).

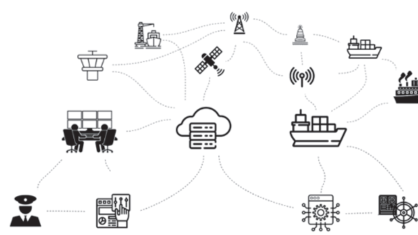

Fig. 1. Highlights the complexity of interaction among entities.

HMI is broadly defined as the study of interactions between humans and machines, with the focus on improving the design and integration of these systems for optimal collaboration (Hoc 2000). Human-Machine Integration emphasizes seamless interaction, while the Human-Machine Interface refers to the physical and digital mediums that facilitate this communication (Bach-y-Rita and W.

Kercel 2003). These concepts are crucial for understanding HMI in the context of complex technological systems like Maritime Autonomous Surface Ships (MASS).

In maritime operations, the integration of human elements in MASS is essential due to the unpredictability of environmental conditions and the need for skilled human decision-making during critical events, such as bad weather or system malfunctions. Human oversight is required for real-time assessments during emergencies, which can significantly enhance operational safety (Ahvenjärvi 2017). Further, ethical considerations, regulatory requirements, and accountability often necessitate the presence of human operators to ensure compliance and uphold the safety of vessels and stakeholders (Hetherington, Flin, and Mearns 2006).

However, HMI in MASS faces significant challenges. Software glitches and algorithmic design flaws pose risks that must be managed with diligent human monitoring and intervention. Human-related factors, such as fatigue and situational awareness, have been linked to maritime accidents, underscoring the need for improved oversight (Mallam, Nazir, and Sharma 2020). These challenges call for a deeper exploration of trust in automation, decision predictability, and the competency required to operate autonomous systems effectively.

2. State of the art

2.1 *Safety Analysis in Human-Machine Interaction*

A systematic literature review was conducted to examine existing safety analysis techniques applied to HMI, focusing specifically on their application within remotely operated systems like MASS. The review addressed three central research questions: (1) What are the types and purposes of various safety analysis techniques? (2) What is the nature and effectiveness of these techniques in enhancing safety within HMI systems? (3) Which domains have these techniques been applied to, particularly concerning teleoperated systems? This paper focuses on preliminary safety analysis approaches within HMI frameworks.

2.2 *Safety Analysis in Remote Operating or Teleoperating Systems*

In the context of remotely operated systems, several methodologies have emerged to analyze safety and mitigate risks. (Clothier, Williams, and Hayhurst 2018) introduce the barrier bow-tie model for risk management in Remotely Piloted Aircraft Operations, which could be adapted for MASS. The model can be combined with other techniques, such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Failure Mode, Effects, and Criticality Analysis (FMECA). Fan et al. 2020 , propose the 4P4F framework for assessing navigational risks in remotely controlled MASS.

CRIOP (Crisis Intervention and Operability Analysis) is another method that has been applied to risk assessment in remotely operated systems. As noted by (Arezes and Boring, 2021.), this method evaluates potential failures and their impacts qualitatively, rather than relying on numerical probabilities. Similarly, dynamic risk-based approaches, such as the one proposed by (Wan et al. 2023), offer frameworks for assessing safety in mixed environments.

STPA (System-Theoretic Process Analysis) has also been adapted for analyzing risks in autonomous systems. (Feng et al. 2019) apply STPA to flight guidance systems, while (Kim et al. 2020) extend it to MASS, analyzing the hazards of different levels of autonomy. (Hoffmann and Diermeyer 2021) apply STPA to teleoperated vehicles, identifying how vehicle feedback can lead to operator error. Chen et al. 2023 further explore the impact of network communication, system control performance, and traffic scenarios on operator behaviour during control transitions in autonomous systems.

3. Methodology

3.1 *STPA for Preliminary Safety Analysis*

In this study, the STPA method is employed as a first step to gain an initial understanding of the safety concerns related to HMI within MASS. This preliminary analysis focuses on identifying potential hazards and unsafe control actions in the system. Based on the insights gathered through STPA, future work will incorporate a Model-Based Systems Engineering (MBSE) approach to provide a more detailed system model and refine safety measures.

4. Result

In this study, the STPA was applied. The method is began by defining what are the purpose of the analysis. In this case, it is to analyse the interaction of remotely operated maritime autonomous surface ship with the focus of ensuring safe and reliable operation of human machine interaction between operator (human), interface and autonomous agent. In this analysis, simplified reference system was use as a means to illustrate the hazards that could rise from unsafe interactions from the three agents. The system loss and system level are defined in Table 1 and Table 2.

Table 1. Losses of system

ID	Losses	Relationship
L-1	loss of life	H-5, H-6, H-7, H-8, H-9
L-2	loss of property	H-1, H-2, H-5, H-6, H-7, H-8, H-9, H-10, H-12
L-3	loss of mission	H-1, H-2, H-3, H-4, H-5, H-6, H-7, H-8, H-9, H-10, H-11, H-12
L-4	loss of reputation (operator)	H-4, H-6, H-8

Table 2. List of hazards

ID	Hazards	Relationship
H-1	loss of communication	L-2, L-3
H-2	loss of signal or data	L-2, L-3
H-3	delays or bugs in transmission of signal or data	L-3
H-4	misinterpretation of information from operator	L-3, L-4
H-5	wrong execution of action by autonomous agent	L-1, L-2, L-3
H-6	wrong execution of action by operator	L-1, L-2, L-3, L-4
H-7	loss of control over the autonomous ship	L-1, L-2, L-3
H-8	emergency response failure	L-1, L-2, L-3, L-4
H-9	navigation system failure	L-1, L-2, L-3
H-10	autonomous controller system malfunction	L-2, L-3
H-11	data inaccuracy	L-3
H-12	system downtime (non operation)	L-2, L-3

Step 1: Model the control structure

Figure 2 shows the structure that defines the human operator, interface, and autonomous control system's roles, duties, and interactions to provide maritime vessel coordination and control.

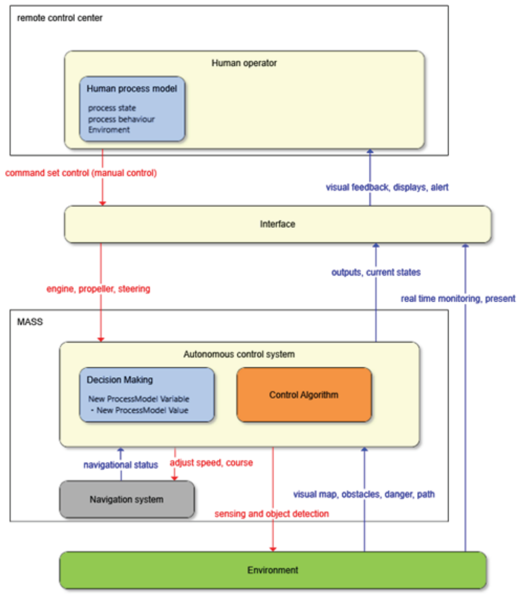

Fig. 2. Control structure of the monitoring and controlling MASS by human operator and autonomous system

The human operator is essential for system monitoring and intervention. They able to provide manual instructions and evaluate interface input. In instances demanding quick human judgement, the operator must be able to manually operate ship systems like steering and speed. The interface's real-time data helps the operator make quick judgements and adapt to changing circumstances and risks.

The interface is essential for human-autonomous control system communication. It reliably transmits operator orders to the autonomous system and provides real-time ship status information. The interface keeps the human operator informed of the vessel's state, providing supervision and control. Through this constant feedback loop, the interface informs the operator of the autonomous system's operations and ship environmental conditions.

The autonomous control system executes operator interface instructions and makes autonomous judgements based on environmental data and navigational needs. It controls ship speed, course, object detection, and navigational rules. The system analyses real-time navigation and sensor data to ensure the ship reacts to external circumstances. In complex and dynamic marine situations, autonomous decision-making is essential for vessel safety and efficiency.

Feedback loops manage these components' interactions, ensuring system safety. For situational awareness, the human operator must continually watch interface feedback, while the autonomous control system uses continuous data inputs to make judgements. Feedback loop interruptions, such as data transmission delays or errors, might impair system safety and cause dangerous circumstances.

Step 2: Identification of UCA

Analysis of Unsafe Control Actions (UCAs) at the MASS Remote Control Centre is necessary for the detection of maritime safety concerns. Certain control actions, known as UCAs (as shown in Table 3), pose risks if carried out incorrectly or at an inconvenient time. These habits, together with their impacts and causes, are examined in this investigation.

UCAs may come from human operators and the autonomous control system, illustrating the intricate relationship between manual and automated operations in MASS. Erroneous commands are a common UCA. This may happen when the human operator or autonomous system issues an improper course or speed order. Such mistakes may cause crashes, groundings, and navigational infractions.

Failure to issue orders is another major UCA. Maritime operations need rapid and precise replies, and missing key directives, such as changing direction to avoid an obstruction, may be dangerous. Delays in command might also be harmful. A delayed evasive manoeuvre may not avert a collision, emphasising the need for control structure decision-making.

A major UCA is feedback misinterpretation. When the human operator misinterprets system interface data, they may overcorrect the vessel's course or miss a danger. This misinterpretation emphasises the requirement for clear and accurate operator decision feedback methods.

MASS control structure UCAs are caused by many sources. A complicated system interface may make it harder for operators to make rapid, precise judgements, increasing the risk of mistakes. Insufficient sensor data or defective decision-making algorithms in the autonomous control system might also cause inaccurate or delayed operations. Operator tiredness, poor training, and cognitive strain reduce the operator's capacity to adapt to dynamic conditions, increasing the probability of UCAs.

Step 3: Loss scenarios for UCA with counter measures

The report's loss scenarios highlight the need of trustworthy autonomous system algorithms, error-proof interface design, and strong human-machine connection (Shown in Table 4a-4c). Enhanced situational awareness, real-time feedback systems, and fail-safe mechanisms should be put in place as a precaution against the possible disastrous consequences, which might include the loss of life, property, and the mission itself.

Loss scenarios caused by human operator faults emphasise the risks of delayed or erroneous orders. Operators may cause crashes, exposure to hazardous circumstances, and engine breakdowns by failing to provide appropriate orders due to poor or late system interface information. In crucial instances, operators being unable to overrule the autonomous system highlights the hazards of over-reliance on automation, which might lead to disastrous results. System interface failures represent considerable hazards. The ship may not respond appropriately to obstacles or engine status changes, which can result in collisions or mechanical malfunctions, due to delays in data transmission or failures to relay critical commands. Further, the potential for loss can be further exacerbated by the vessel being directed into hazardous situations as a result of incorrect

Table 3. List of identified UCA

Control Action	Not providing causes hazard	Providing causes hazard	Too early, too late, out of order	Stopped too soon, applied too long

command set control (manual control) Human operator -> Interface	(UCA-1) Operator fails to send a necessary command due to a lack of timely information from the interface. (UCA-2) Human operator is unable to override or input command control for ACS due to Interface restrictions	(UCA-3) Operator sends an incorrect command due to misinterpretation of data from the Interface (UCA-4) Operator inputs an incorrect command due to a confusing or unclear interface design	(UCA-5) Operator sends a command at the wrong time due to delay in the transmission of data to the interface	
engine, propeller, steering Interface -> ACS	(UCA-6) Interface fails to relay critical commands from the operator, leading to autonomous control system inaction	(UCA-7) Interface relays incorrect commands to the ACS due to software bugs or glitches	(UCA-8) Interface sends outdated or stale commands, the ASC to execute inappropriate actions	
adjust speed, course ASC-> Navigation system	(UCA-10) ACS fails to provide control action to the Navigation system due to malfunction of the algorithm to adjust speed and course	(UCA-11) ACS sends incorrect navigational commands due to faulty algorithms	(UCA-12) ACS sends commands too early or delay to the navigational system to adjust speed, course	(UCA-14) ACS fails to adapt to sudden changes in the environment, such as weather or traffic conditions
sensing and object detection ACS -> Environment	(UCA-15) ACS fails to send necessary navigational commands in response to environmental changes.	(UCA-17) ACS misinterprets environmental data, causing unsafe maneuvers.	(UCA-18) delayed in transmitting data from sensors to the ACS causing inaccurate decision	(UCA-19) ACS does not account for environmental regulations, resulting in illegal or unsafe actions.

commands caused by software flaws or obsolete data.

Autonomous system failures add risk. For instance, in which the system fails to accurately alter the ship's speed or course, the vessel may deviate from its intended course, overexert its engines, or violate navigational regulations. These failures show that autonomous control systems require trustworthy algorithms and fail-safe measures.

The suggested loss scenarios emphasise the significance of improving human-machine interaction dependability, autonomous system accuracy, and safety precautions. These precautions are essential for Maritime Autonomous Surface Ship safety.

Table 4a. UCA-1

Control Action	command set control (manual control)
UCA-1	Operator fails to send a necessary command due to a lack of timely information from the interface.

ID	Loss Scenario
LS-1	Collision with another vessel due to missing navigational updates.
LS-2	Exposure to severe weather conditions, causing structural damage
LS-3	Engine failure due to unnoticed critical engine status

Table 4.b UCA-2

Control Action	command set control (manual control)
UCA-2	Human operator is unable to override or input command control for Autonomous control system due to Interface restrictions

ID	Loss Scenario
LS-4	Collision with an object because the operator can't take manual control.
LS-5	Failure to perform a emergency maneuver which could lead to accident
LS-6	

	inability to take over which could lead to disaster

Table 4.c UCA-3

Control Action	command set control (manual control)
UCA-3	Operator sends an incorrect command due to misinterpretation of data from the Interface
ID	Loss Scenario
LS-7	Setting the ship on a collision course due to navigational error
LS-8	Overstressing the engines and causing mechanical failure

To prevent identified loss scenarios in Maritime Autonomous Surface Ships (MASS), safety constraints must ensure reliable autonomous algorithms, error-proof interfaces, and robust human-machine interaction. Real-time feedback and enhanced situational awareness are essential for timely decision-making, while fail-safe mechanisms must guarantee safe system states during failures. These constraints collectively enhance system resilience, mitigating risks from human error, interface failures, and autonomous malfunctions (below shown Table 5 consist of constrains and countermeasure required to address the unsafe conditions).

Table 5. List of System constraints and system countermeasure.

ID	Constraints	Countermeasures	Relationship
SC-1	Must have adequate redundancy to provide the alternative option	Deploy backup systems that automatically activate upon primary system failure to maintain operations.	H-1
SC-2	implement error detection to recover the data or signals	Use error-checking algorithms to detect and correct corrupted data or signal loss.	H-2
SC-3	provide adequate real time and timely feedback	Deliver real-time system updates and feedback to operators to ensure situational awareness.	H-3
SC-4	implement protocol to ensure the operator confirms the information before executing the actions	Require operator confirmation before executing critical tasks to avoid accidental operations.	H-4, H-6
SC-5	implement fail-safe mechanism to the autonomous decision making to prevent the incorrect actions	Introduce automated system resets or safe shutdown procedures in case of decision-making failures.	H-5
SC-6	implement validation protocol to ensure that all operator input is in acceptable range before execution	Validate operator inputs to ensure they fall within acceptable and safe operational ranges.	H-6

6. Discussion

Traditional risk assessment methods, such as failure mode-based approaches, often rely on predefined checklists, which may not fully capture risks in highly automated systems like MASS. This study applies STPA, which examines system structures, interactions, and feedback loops, making it suitable for human-automation collaboration. Based on the results, it identifies UCA and inadequate feedback that may emerge in MASS, where automation influences situational awareness, cognitive workload, and decision-making. Modern safety perspectives, such as FRAM, resilience engineering, and other dynamic risk assessment tool, focus on supporting system performance under real-world conditions. By integrating these principles, STPA enables a proactive approach to safety, ensuring robust human-machine interactions as automation levels increase. However, this study relies on secondary data for STPA, which may limit the accuracy and practical relevance of the results, as it does not account for the complexities of real-world operational scenarios.

7. Future research

Future research should focus on the actual implementation and integration of STPA with MBSE to provide a robust methodology for safety analysis in HMI within MASS. A comprehensive framework that incorporates both methods will offer enhanced risk identification, system modeling, and overall safety assurance. This integration would allow for iterative safety checks during the system design phase and after deployment, ensuring continuous risk management throughout the system lifecycle. Moreover, future studies should gather and analyze primary data from real-world MASS operations. This will enable more accurate safety analysis, reflecting the true operational environment of remotely operated vessels. The use of empirical data will strengthen the analysis and offer more practical insights for the development of safe and effective HMI in maritime systems. Finally, expanding the focus of future research to include MBSE will allow for a deeper investigation into system requirements, enhancing the ability to predict and mitigate risks in HMI. Integrating MBSE with STPA will provide a more structured approach for addressing complex safety concerns and refining risk management strategies for maritime autonomous systems.

8. Conclusion

This paper has demonstrated the application of STPA for safety analysis in the context of Human-Machine Interaction (HMI) within the Remote Control Centre of Maritime Autonomous Surface Ships (MASS). The findings highlight critical hazards associated with human-machine collaboration, including potential delays in operator response, misinterpretation of data, and failures in automated systems. Addressing these challenges requires a combination of enhanced operator training, refined system design, and robust safety mechanisms. While the study relied on secondary data, it provides a valuable foundation for understanding safety risks in HMI for MASS. Future research integrating primary data and advanced methodologies such as MBSE will further strengthen safety frameworks, ensuring reliable and secure operations in autonomous maritime environments. The integration of STPA with MBSE offers a promising direction for continuous improvement in safety analysis and risk management strategies for MASS.

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