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# **University of Southampton**

Faculty of Engineering & Physical Sciences

Human Factors Engineering

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Department of Civil, Maritime and Environmental Engineering

## **Investigating decision-making in human-machine teams for the operation of Maritime Autonomous Surface Ships**

by

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Thesis for the degree of Doctor of Philosophy

June 2025

# University of Southampton

## Abstract

Faculty of Engineering & Physical Sciences

Human Factors Engineering

Doctor of Philosophy

Investigating decision-making in human-machine teams for the operation of Maritime Autonomous Surface Ships

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The introduction of uncrewed Maritime Autonomous Surface Ships is fundamentally changing how ships are operated. Due to the remote nature of MASS, decision-making will become more challenging as operators will lack the physical cues they would have had onboard a vessel, so they will be more dependent on the technological systems. Additionally, the higher levels of automation in MASS are changing the role of the operator within the human-machine team to mainly a supervisory role, as they will be monitoring the automated systems and transitions of control. It is therefore important to explore how system design can support operators' ability to monitor the automated systems effectively and maintain their situational awareness, so that they can make appropriate decisions during operations. This thesis investigates how decisions are made in human-machine teams, to explore how MASS operators' decision-making at Remote Control Centres can be supported. Firstly, to identify the decision-making factors that need to be explored, a systematic literature review was conducted to develop a model of seven key factors involved in decision-making in human-machine teams. The seven decision-making factors were then used as the foundation of the research programme and a mixed methods approach was used to investigate each factor. The mixed methods approach included using the Perceptual Cycle Model framework, Systematic Human Error Prediction and Reduction Approach, the Risk Management Framework and other human factors methods to investigate the decision-making factors. The methods were employed to understand how decision-making can be supported through the system's design. This resulted in design considerations and principles, and mitigation strategies that could be considered when creating future MASS system concept designs. From the findings of the application of these methods, a user-centred design framework has been created for industry, to facilitate the application of the methods in future design of novel systems to support HMT decision-making. The research has demonstrated how human factors methods can be applied prospectively to generate user-centred design concepts before the users or systems exist.

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# Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

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2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
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## Journal Articles

Lynch, K. M., Banks, V. A., Roberts, A. P. J., Downes, J., Radcliffe, S. & Plant, K. L. (2023). The application of a system-based risk management framework and social network analysis to the Maritime Autonomous Surface Ship system: Who are the decision-makers in the wider system? *Human Factors and Ergonomics in Manufacturing & Service Industries*, 33, 395-429.

Lynch, K. M., Banks, V. A., Roberts, A. P. J., Radcliffe, S. & Plant, K. L. (2023). Maritime autonomous surface ships: can we learn from unmanned aerial vehicle incidents using the perceptual cycle model? *Ergonomics*, 66, 772-790.

Lynch, K. M., Banks, V. A., Roberts, A. P. J., Radcliffe, S. & Plant, K. L. (2024). What factors may influence decision-making in the operation of Maritime autonomous surface ships? A systematic review. *Theoretical Issues in Ergonomics Science*, 25, 98-142.

## Conference Papers and Presentations

Research Thesis: Declaration of Authorship

Lynch, K. M., Banks, V. A., Roberts, A. P. J. & Plant, K. L. (2022). Analysis of an Unmanned Aerial Vehicle accident using the Perceptual Cycle Model. Presentation given at the *13<sup>th</sup> International Conference on Applied Human Factors and Ergonomics*. July, New York, USA.

Lynch, K. M., Plant, K. L., Roberts, A., Banks, V. A. & Taunton, D. (2023). Investigating decision-making in the operation of Maritime Autonomous Surface Ships using the Schema World Action Research Method. *Proceedings of the First International Symposium on Trustworthy Autonomous Systems*. Edinburgh, United Kingdom: Association for Computing Machinery.

Lynch, K. M., Young, M. S., Taunton, D., Banks, V. A., Roberts, A. P. J. & Plant, K. L. (2024). Development of a Behavioural Markers System for Maritime Autonomous Surface Ship Operations. Presentation given at the *Ergonomics and Human Factors Conference*. April, Kenilworth, UK

Lynch, K. M., Young, M. S., Taunton, D., Banks, V. A., Roberts, A. P. J. & Plant, K. L. (2024). How can we support uncrewed Maritime Autonomous Surface Ship operators in their decision-making? Presentation given at the *Royal Institute of Naval Architects Human Factors Conference*. October, Wageningen, Netherlands.

Contribution to information paper submitted to International Maritime Organisation

Institute of Marine Engineering, Science & Technology and International Transport Workers' Federation (2025), Development of a Behavioural Markers System for Maritime Autonomous Surface Ship Operators. *International Maritime Organisation sub-committee on Human Element, Training and Watchkeeping 11<sup>th</sup> Session*. (under review)

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## Acknowledgements

This work was funded by the Engineering and Physical Science Research Council and an industrial sponsor Thales UK. This work could also not have been completed without the participants who gave up their time to take part in the studies and the subject matter experts who kindly gave up their time to review many parts of this work.

I would like to thank my supervisors, first Dr Katie Plant for all her support throughout my studies, I definitely would not have been able to complete this without your help. On the days I thought I would not be able to finish it you always provide encouragement, reassurance and great ideas to help me through it and pick me up. Thank you for all the time you have spent reviewing all my drafts and providing me with valuable feedback I have learnt so much through this process from you. Likewise, thank you Dr Vicky Banks, I will always be grateful for your support and guidance, especially during the start of my PhD when I was quite lost. Thank you for always making the time to reassure me and provide me with ideas when I hit one of the many bumps in the road. To my other supervisors along the way, Dr Jon Downes, Professor Mark Young, Dr Aaron Roberts and Dr Dominic Taunton, thank you for all your guidance and feedback during the different stages of my research. I also wanted to thank Dr Mark Chattington and Professor Neville Stanton, for the advice and guidance they have both offered me, particularly at times when I was not sure which direction to head in.

I would also like to thank the team at SeaBot Maritime, Gordon, Jon and Ifor for all their help and the opportunity to get hands on with MASS operations, some of the most fun memories of doing my PhD was taking part in the training courses down at the National Oceanography Centre. Siobhan thank you for being there to provide moral support whilst you were also doing your PhD too. Siobhan, you've been a great help at keeping me going and I had the best time with you and Katie Parnell in New York at my first conference and thank you Katie for your help and guidance too. Thank you to the HMT team and others at Thales, Erinn, Katie, James, Emily, Tommy and Charlotte thanks for all your support in the final stages of my PhD.

Completing my PhD has definitely been a journey of up and downs, but I have been very fortunate to have the best people to lean on during that journey. My 'Southampton Crew', Jo, Alex, Alice, Hugo, James and Caroline thank you all for your support and encouragement and always providing me with opportunities to go off on adventures with you all. Thank you, Kyle for all your support and always making me laugh even when things weren't going well. Lastly, I want to thank my Mum and Dad for all their support and encouragement along the way and always being there whenever I needed someone to pick me up, you've been the best. You've both always had faith in me and that belief has helped me get to where I am today.

## Definitions and Abbreviations

ATOLS .....	Automatic Take-Off and Landing System. Automated system on uncrewed aerial vehicles which controls take-off and landing.
Automation .....	The execution by machine of a function previously carried about by a human.
Autonomy .....	The ability of an engineering system to make its own decisions about its actions while performing different tasks, without the need for the involvement of an exogenous system or operator.
AVDC.....	Air Vehicle Display Computer. A human-machine interface used to monitor an uncrewed aerial vehicle.
BMS .....	Behavioural Markers System. A collection of behavioural markers that can be used to assess nontechnical skill performance.
DSS.....	Decision Support System. A system which used to support human operators by giving them information to aid their decision-making, this can be in the form of alerts or recommendations.
GCS .....	Ground Control Station. Ground based remote control centre where humans operate and monitor uncrewed aerial vehicles.
HMI.....	Human-Machine Interface. A user interface or dashboard that connects a person to a machine, system, or device.
HMT .....	Human-Machine Team. A team which consists of both human and machine agents who control and monitor the system.
HTA .....	Hierarchical Task Analysis. A Human Factors method which describes an activity in terms of its specific goals, subgoals, operations, and plans.
MASS .....	Maritime Autonomous Surface Ship. A ship which, to a varying degree, can operate independently of human interaction.
PCM .....	Perceptual Cycle Model. A naturalistic decision-making model describes the reciprocal, cyclical, relationship that exists between an operator and their work environment; depicting the interaction between internally held mental schemata and externally available environmental information as contributors to decisions and actions.
SA.....	Situation Awareness. Describes the decision maker's perception of the state of the environment.

## Definitions and Abbreviations

- RCC ..... Remote Control Centre. Remote control centre where humans operate and monitor uncrewed aerial vehicle (ground based) or maritime autonomous surface ships from (shore-side or on a host ship).
- RMF ..... Risk Management Framework. A sociotechnical systems approach that is used to show the interaction between the different system levels.
- SHERPA ..... Systematic Human Error Reduction and Prediction Approach. A Human Factors method used to provide guidelines for human error reduction and quantification in a wide range of human-machine systems.
- Transparency ..... The transparency of an automated system describes the degree to which the human is aware of what the system's processes are and their understanding of how the system makes decisions.
- Trust ..... A human's trust of an automated system is a function of the system's predictability and dependability, and their faith in that system.
- UAV ..... Uncrewed Aerial Vehicle. Is an aircraft that operates without humans onboard and is operated from a ground control station.
- UCD ..... User-Centred Design. An approach that prioritises the users needs during system design.

# Chapter 1 Overview, Motivations, Aims and Objectives

## 1.1 Background

Uncrewed Maritime Autonomous Surface Ships (MASS) are being introduced as they have the potential to increase safety and mitigate the shortfall of seafarers that is anticipated in the future (Kim and Schröder-Hinrichs, 2021). MASS operators will be operating and/or monitoring the ships for their whole journey from Remote Control Centres (RCCs) either on a host ship or shore-side control centre (Hogg and Ghosh, 2016). The operation of MASS from RCCs has the potential to increase reliability and safety by removing the need for onboard operators whilst also giving operators a better working environment (Norris, 2018; Ramos et al., 2018). As MASS are developed they bring a potentially wide range of applications for the military, search and rescue, hydrographic surveying and disaster relief (Norris, 2018). Another advantage of MASS is their enhanced manoeuvrability and deployability in shallow waters, as they can be made lower weight and more compact than a crewed ship (Liu et al., 2016). There are however conflicting drivers within the system as using MASS could reduce costs and smaller investments in the technology may be made which could lead to safety risks or in the case of fields where safety is the driver in adopting MASS larger investments could lead to be improved safety versus conventional ships (Li and Fung, 2019).

The concept of operations for MASS are relatively new, and although the majority of MASS are still in development and trial phases, some are operational and use multiple levels of automation. Two examples of remotely operated ships are SEA-KIT International's Maxlimer and XOcean's remotely operated vessel, both of which are used for hydrography surveys (Maritime Coastguard Agency, 2020). An example of an autonomous MASS is the Mayflower 400, a research vessel part of a joint project between MSubs, Plymouth University, ProMare and IBM (Maritime Coastguard Agency, 2020). Other examples of MASS are Thales' and L3 Harris' MASS, the Halcyon, which is used for mine countermeasures (Thales UK Ltd, 2018) and L3 Harris' C-Cat 3, which is used for shallow water surveys inshore and coastal waterways and can be manually controlled or programmed to follow an assigned route (L3 Harris Ltd, 2021).

There is also interest in using MASS for merchant shipping as using autonomous ships is expected to be safer, more efficient, and cheaper to run as an operator at an RCC could monitor more than one ship, and the ships have the potential to reduce workload (Ahvenjärvi, 2016; Dybvik et al., 2020; Rødseth and Nordahl, 2017). The Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project has investigated merchant shipping using autonomous navigation systems to assess its technical, legal and economic feasibility (Burmeister et al., 2014a). The project looked at the uncrewed autonomous operation of dry bulk carriers during deep-sea voyages; the ships would then

be handed over to an onboard crew for berthing and de-berthing (Burmeister et al., 2014a). During the ship's deep-sea voyage, it would be monitored from a shore-side RCC where an operator would be responsible for monitoring several ships and could carry out tasks such as updating the ship's route (Burmeister et al., 2014a).

The International Maritime Organisation (IMO) has defined four degrees of autonomy for MASS (International Maritime Organisation, 2021), see Table 1.1. At degree one, the ship has seafarers on board but some operations are automated, while at degree two the ship can be remotely controlled but there are still seafarers onboard (International Maritime Organisation, 2021). For degree three there are no longer seafarers onboard and the ship is operated from another location such as a shore-side control centre or a host ship (International Maritime Organisation, 2021). Lastly, at degree four there are no longer seafarers on board the ship and the ship can make decisions and execute operations by itself without human involvement (International Maritime Organisation, 2021).

Table 1.1 - Degrees of autonomy for MASS as established by the International Maritime Organization (International Maritime Organisation, 2021).

<b>Degree of Autonomy</b>	<b>Ship Control</b>	<b>Description</b>
1	Ship with automated processes and decision support	Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.
2	Remotely controlled ship with seafarers on board	The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
3	Remotely controlled ship without seafarers on board	The ship is controlled and operated from another location. There are no seafarers on board.
4	Fully autonomous ship	The operating system of the ship is able to make decisions and determine actions by itself.

In addition to the degrees of autonomy the European Defence Agency's Safety and Regulations for European Unmanned Maritime Systems (SARUMS) group has defined five levels of control for MASS (see Table 1.2); the level of control may range between level one (manually operated by a human operator) to level five (the system operates autonomously with no human involvement) (Maritime UK, 2020). A ship may have certain functions that are highly automated and require a human to only

monitor the system (level four of control) (Maritime UK, 2020). Other functions may have a lower level of automation and require operators to make decisions from a selection of proposed options (level two of control) (Maritime UK, 2020). Therefore, within the degrees of autonomy a MASS system could be operated at different levels of control/automation.

Table 1.2 - Levels of control for MASS operation (Maritime UK, 2020).

Level	Name	Description
1	Operated	Under Operated control all cognitive functionality is within the human operator. The operator has direct contact with the MASS over e.g., continuous radio and/or cable. The operator makes all decisions, directs and controls all vehicle and mission functions.
2	Directed	Under Directed control some degree of reasoning and ability to respond is implemented into the MASS. It may sense the environment, report its state and suggest one or several actions. It may also suggest possible actions to the operator, such as e.g., prompting the operator for information or decisions. However, the authority to make decisions is with the operator. The MASS will act only if commanded and/or permitted to do so.
3	Delegated	The MASS is now authorised to execute some functions. It may sense environment, report its state and define actions and report its intention. The operator has the option to object to (veto) intentions declared by the MASS during a certain time, after which the MASS will act. The initiative emanates from the MASS and decision-making is shared between the operator and the MASS.
4	Monitored	The MASS will sense environment and report its state. The MASS defines actions, decides, acts and reports its action. The operator may monitor the events.
5	Autonomous	The MASS will sense environment, define possible actions, decide and act. The Uncrewed Vessel is afforded a maximum degree of independence and self-determination within the context of the system capabilities and limitations. Autonomous functions are invoked by the on-board systems at occasions decided by the same, without notifying any external units or operators.

The level of automation is important as it describes the level of human involvement in the system. As the level of automation increases, it changes the operator's involvement from direct control to

supervisory control (Sheridan et al., 1989). Although humans will be removed from onboard the ship, the problems which are usually labelled 'human factors issues' or 'human error' will not necessarily be removed, as there will still be humans involved in part of the system (Ahvenjärvi, 2016; Hogg and Ghosh, 2016; Porathe et al., 2014). It has been suggested that by removing the crew from onboard, there will be an increase in navigational safety; however, this could just change the types of 'human errors' found in the system (Hogg and Ghosh, 2016; Wróbel et al., 2017).

This thesis will focus on degree three, where the operator is operating or monitoring the ship from another location, an RCC (a host ship or shore-side control centre) and there are no personnel onboard the ship. This thesis focuses on degree three as there are currently different trial MASS operating uncrewed and there is a need to explore how the increase levels of automation and the remote operation of MASS may affect decision-making (Maritime Coastguard Agency, 2020).

Although there are many types of MASS the work in this thesis is from a UK setting focusing primarily on medium sized high energy MASS that conducted coastal operations (e.g., surveys) such as Fugro's Blue Shadow (Millar, 2021). As in coastal waters are a higher risk environment due to the increased number of different types of vessels and a more complex underwater environment (Filisetti et al., 2018; Hu and Zhang, 2012).

Whilst this thesis will only focus on uncrewed MASS operations (degree three of autonomy), it will investigate the different levels of automation that could be used to operate MASS with a focus towards the higher levels of control. The introduction of more highly automated uncrewed MASS will change the role of human operators to supervisors (Man et al., 2018b; Ramos et al., 2018; Wahlström et al., 2015). The change in dynamic will mean that the system will be more teammate-like than tool-like, which will create a Human-Machine Team (HMT) between the operator and system (Dominguez-Péry and Vuddaraju, 2020; Liu et al., 2022a). The thesis aims to explore on how higher levels of automation may impact the decision-making process of HMT, as the decision-making will be shared between the operator and system. This thesis focuses on the operator's interaction with the MASS and not the decision-making of any other crew e.g., maintenance crew that may also be working with the MASS.

The change to the operators' location and the use of more highly automated systems could potentially lead to new system errors due to the lack of proximity between the human and automated system (Porathe et al., 2014). It is expected that the operator at the RCC will be a fail-safe in case the ship encounters an unexpected situation; the operator would then step in and remotely control the ship to satisfy legal requirements that a human is still in charge (Dybvik et al., 2020). This demonstrates that whilst the operators may no longer be present onboard, their involvement has not been entirely removed, the nature of their role within the system will have changed. The operator will still be an important part of the system as they will be a backup to the automation and

therefore, the design of MASS systems will need to consider how to support the operator to reduce the likelihood of new system errors being introduced.

The operators at RCCs may lack Situation Awareness (SA), changing the nature of distributed SA across the HMT due to no longer being able to sense the ship's environment, which will make it more difficult for the operators to make appropriate decisions (Porathe et al., 2014; Wahlström et al., 2015). Operators will lack environmental information, such as the noise coming from physical changes of the rudders and main propellers, which can be critical in determining the system faults (Ahvenjärvi, 2016). Operators will also have to consider the possibility that sensors may be faulty, so they may not be given accurate information from the automated system (Hogg and Ghosh, 2016). This could make it difficult for operators to diagnose system faults, as these systems will be highly complex, and operators will lack proximity to them (Hogg and Ghosh, 2016). Another challenge for operators will be forming accurate mental models of the automated system they are working with, which would affect their ability to maintain their SA; i.e., how the operator interprets perceived information and predicts future states (Endsley, 2011; Matthews et al., 2020; Warren and Hillas, 2020). Forming accurate mental models of a teammate, including a machine teammate can also affect the ability of a team to work safely and efficiently (Grimm et al., 2023). The higher levels of autonomy are also changing how the operator will work with this system, which may have implications for social interactions between the operator and system needed for teamwork in a HMT (Walliser et al., 2019).

Also, operators may become overloaded with information from the ship due to the number of sensors required to operate the ships remotely and/or autonomously, and it may be more difficult to decide what information is relevant (Dybvik et al., 2020; Man et al., 2014; Porathe et al., 2014; Wahlström et al., 2015). There could be problems with connection delays between a MASS and the RCC, giving operators less time to make potentially safety-critical decisions (Man et al., 2018b). Also, there are many issues associated with humans monitoring automated systems, such as operators becoming 'out of the loop' and over trusting the automated system, leading to inadequate monitoring and accidents, which will be discussed in more detail in Chapter 2 (Endsley and Kiris, 1995; Hoff and Bashir, 2015; Parasuraman and Riley, 1997). These different issues will make it more difficult for operators at RCCs to make appropriate decisions and the use of higher levels of autonomy could increase these challenges, as the operator is moved further from the decision-making process (Man et al., 2016; Porathe et al., 2014).

Although the human involvement of the system will change with the higher levels of autonomy, the operator's role is still a key part of the system, and their requirements need to be investigated to overcome these decision-making challenges. A User-Centred Design (UCD) approach is needed to understand operators' requirements for working within a HMT for the operation of MASS, such

approaches can be used to explore the interactions within the HMT, to ensure the system design supports the operator and system to work effectively together (Harris, 2007; Hsieh et al., 2024). A UCD approach will ensure that MASS systems are designed with a focus on the user how they will operate the systems rather than just focusing on developing the technological capabilities of a system (Harris, 2007; Hsieh et al., 2024). It has been highlighted that the use of UCD approaches in the development MASS will improve operator's ability to perform their tasks, their user experience and integrate systems with the human teams to form HMTs (Lützhöft, 2023). It is also important that these UCD approaches are applied early within the design process to reduce the costs associated with design changes later in the process (Stanton et al., 2017b). This thesis demonstrates how a mixed method approach can be used to design MASS systems, by using UCD approaches early in the design process to aid in the development of conceptual designs that support decision-making within an HMT. It is necessary to investigate the factors involved in decision-making within HMTs for the operation of uncrewed MASS; to understand how the operator's decision-making processes can be supported by investigating these decision-making factors using a variety of user-centred methods. A mixed-methods approach is required to explore the different aspects of the MASS system as it is a complex sociotechnical system.

When investigating the design of complex sociotechnical systems, it is important not only to analyse the interactions between the operator and system but to consider how the wider influences will affect the system's operation (Hulme et al., 2019; Rasmussen, 1997; Salmon et al., 2017).

Sociotechnical systems' analyses can be conducted using different system lenses, at the micro level to consider how an operator can be supported through their equipment design, at the meso level by analysing organisational influences and at the macro level the regulatory and other much wider system influences (Banks et al., 2019; Parnell et al., 2017). This thesis uses a UCD approach that integrates methods at the micro, meso and macro system levels to show how all levels of a complex sociotechnical system can be explored when designing future systems. The mixed methods approach will ensure that methods that use each the different system lens (micro, meso and macro) are applied to MASS to understand the how decision-making will be affected.

## **1.2 Aims and Objectives**

This PhD aims to investigate how decisions are made in HMTs using a mixed methods approach to explore how systems can be conceptually designed and evaluated to support decision-making within HMTs during the operation of MASS. To meet this aim, the following objectives have been developed:

1. Understand the factors involved in decision-making in HMTs and the design considerations for each of these factors and how decision-making in HMTs has previously been investigated in maritime and other domains where automation is more established (e.g., aviation).
2. Investigate the tasks and decisions involved in operating MASS using human factors methods, to understand how operator decision-making can be supported through system design principles and mitigation strategies.
3. Explore what behavioural competencies are required to support teamwork in HMTs
4. Conduct a sociotechnical analysis to understand how MASS are currently regulated and provide recommendations on how the system may be strengthened.
5. Develop a design framework for industry, outlining how the UCD methods could be used in design of novel automated systems such as MASS.

### **1.3 Overview of Thesis**

#### **1.3.1 Chapter 1 – Overview, Motivation, Aims and Objectives**

This chapter includes background information about MASS, including the defined degrees of autonomy and levels of control and an introduction to the Human Factors challenges involved in their operation from RCCs. Outlined in this chapter are the aims and objectives of the thesis, an overview of the thesis with summaries of each of the chapters and the contribution to knowledge.

#### **1.3.2 Chapter 2 – What factors may influence decision-making in the operation of Maritime Autonomous Surface Ships? A systematic review**

In this chapter, a systematic literature review was conducted, focusing on decision-making to generate insights into operating uncrewed vehicle platforms and design considerations for MASS. It is anticipated that introducing higher levels of autonomy and operating MASS uncrewed from RCCs will create challenges for decision-making due to the operator's lack of proximity to the platform as the decision-making will be shared between the system and human operator. Seven factors in decision-making were revealed: decision support systems, trust, transparency, teams, task/role allocation, accountability and SA. A Network Model, the decision-making factors in HMT model, was developed to show the interconnections between these factors. These factors will form the foundation of the research programme, and each factor will be explored further using a range of methods in the other chapters of this thesis. In this chapter the decision-making factors in HMT model was then applied to a case study of an Uncrewed Aerial Vehicle (UAV) accident. The purpose was to demonstrate the utility of the model to real-world scenarios and show how each factor applied within the HMT.

Design considerations and future research avenues were generated from the literature for each factor within the model. The methods used in the following chapters (Chapters 3 to 8) each investigated the factors within the network model generated in this chapter. The findings and methods from investigating the factors from each chapter were then used to create a UCD design framework in Chapter 9 and to update the decision-making factors in HMT model initially created in this chapter in Chapter 10.

### **1.3.3 Chapter 3 - Maritime Autonomous Surface Ships: Can we learn from Uncrewed Aerial Vehicle incidents using the Perceptual Cycle Model?**

This chapter investigated the underlying decision-making processes of operators of uncrewed vehicles using the Perceptual Cycle Model (PCM) as a framework to model naturalistic decision-making. The PCM was applied to the UAV case study to further explore all seven HMT decision-making factors found in Chapter 2 and to extend the developed decision-making factors in HMT model. The UAV case study applied in Chapter 2 was utilised here due to the similarities with MASS operations as they are also controlled from RCCs. Two PCMs were developed: one to demonstrate what actually happened and one to demonstrate what should have happened (i.e., work-as-done versus work-as-imagined). A comparison of the models demonstrated the importance of operator SA, clearly defined operator roles, appropriate training and interface design in making decisions when monitoring uncrewed systems from RCCs. It is anticipated that these factors will also be applicable in the continued design and development of future MASS systems. The application showed how an operator's mental model can be affected when operating remotely and how for decision-making, it is necessary to consider the design of the system to support an operator in developing an accurate mental model. The retrospective application of the PCM showed how it can be applied to generate user-centred insights into decision-making in HMTs.

### **1.3.4 Chapter 4 - Generating design and training principles for supporting decision-making in the operation of uncrewed Maritime Autonomous Surface Ships using the Schema World Action Research Method**

This chapter used the Schema World Action Research Method (SWARM) to explore the decision-making process of MASS operators to understand how it can be supported when operating highly automated MASS from RCCs. The chapter further investigated all the factors within the decision-making factors in HMT except for accountability and their interconnections with other factors and showed how the PCM framework can be used to generate UCD insights into future systems. There are various decision-making challenges associated with operating MASS from RCCs, including how to support operators in maintaining their SA due to the lack of physical cues and how to aid operators in monitoring the highly automated systems for long periods. Seven MASS operators and four subject

matter experts were interviewed using the semi-structured SWARM interview technique. The results identified four key areas for operator decision-making: the ability to develop appropriate expectations of the automation, the operator's supervisory role, the challenges in operating uncrewed and being able to handle system faults. Design and training principles for decision-making were then generated from the data, including: design considerations such as the system's transparency, the types of display indications needed and designs to support system monitoring, and training and experience for the development of appropriate schema. Applying SWARM demonstrated how it can be used to generate user-centred design and training principles before the system or users exist. The findings showed the difficulties operators may have in forming accurate mental models when operating due to the change in their role and the types of world information they will have available.

### **1.3.5 Chapter 5 – Principles for engendering trust in human-machine teams: exploring Maritime Autonomous Surface Ship operators' trust using the Trust-Schema World Action Research Method**

The operation of uncrewed MASS has implications for operators' trust due to the lack of proximity to the MASS, so operators will be highly dependent on the information provided by digital systems. Also, trust was shown to be a key factor within the decision-making factors in HMT model. Trust can affect operators' use of automated systems and their ability to monitor the systems effectively. Therefore, it was necessary to consider how to support operators in trusting MASS systems appropriately so as not to over- or under-rely on the systems. The Trust variant of SWARM was used to interview operators and subject matter experts. The Schema Action World (SAW) taxonomy was applied to the analysis, which is underpinned by the PCM. It was found that seven key factors influenced trust: "Display Indications", "System Monitoring", "Technological Conditions", "Situation Assessment", "Artefacts", "Direct Past Experience" and "Navigate". These key trust factors, along with the four key areas identified in Chapter 4, were used to generate principles for the design of MASS systems and the training of MASS operators to promote calibrated trust. These principles included ensuring operators have experience and training in handling system faults and being provided with multiple sources of information to cross-reference. Investigating trust using the trust variant of SWARM demonstrated how design and training principles can be generated for forming calibrated trust in the early stages of a system's design. The design principles generated have shown the types of world information that could aid operators in being able to assess whether the system information is as expected and how much that information should be trusted. In addition, training principles were generated, which could be used to supplement the formation of calibrated trust after considering the system design. The findings have shown further interconnections between the trust factor and the other factors within the decision-making factors in HMT model.

### **1.3.6 Chapter 6 – Predicting design induced errors in a Maritime Autonomous Surface Ship Remote Control Centre**

This chapter aimed to investigate what errors may occur during the operation of an uncrewed MASS from a RCC at the end-user level of the system. A user-centred approach was applied at the early design stages of a system to investigate how system design can induce errors. This was achieved by using Hierarchical Task Analysis (HTA) to describe the operator's tasks during an environmental survey and then the Systematic Human Error Reduction and Prediction Approach (SHERPA) technique was applied to predict where errors may occur during operation. The use of HTA and SHERPA further investigated the decision-making factors in HMT (such as decision support system design, transparency, communication and task/role allocation) to further understand their influences. A HTA was developed from system documentation and observations of software testing to show the tasks involved in operating an uncrewed MASS using a Human Machine Interface (HMI) at a RCC for an environmental survey. The HTA for an environmental survey showed that many of the tasks performed during a normal operation will be checking tasks with only a few HMI inputs required if the operation is occurring as expected. The results of applying SHERPA showed that there were many errors associated with operating a HMI located at an RCC, although most had a low likelihood of occurring. Design-based remedial strategies were then suggested for the key errors identified, which included increasing the saliency of alerts, prompting operators to perform checks in response to certain alerts and changes to the design of other HMI elements. This approach showed how HTA and SHERPA can be applied at the early stages of system design to explore potential design-induced errors that could occur when designing a MASS by considering the users perspective.

### **1.3.7 Chapter 7 - Developing Human-Machine Team competencies: a Behavioural Markers System for Maritime Autonomous Surface Ship Operations**

Developments in technological systems mean that they are becoming more teammate-like than tool-like and therefore operators and systems will need to work co-operatively as an HMT. This chapter developed a Behavioural Markers System (BMS) for HMTs for the operation of MASS from RCCs to support the design and evaluation of future MASS systems and to assess operators' ability to work with machine teammates. The development of the BMS explored the decision-making factors in HMT model including teams, transparency, task/role allocation, SA and decision support systems. The BMS will also be used to support the development of propose new competencies for future training standards and guidance when working within an RCC team. The BMS was developed using existing literature for human-human cooperation to understand which behaviours were relevant for an HMT and what modifications needed to be made for a machine teammate. The majority of the human team behaviours were found to be relevant to HMTs and the BMS developed consists of nine main categories: closed-loop communication, decision-making, performance monitoring, backup

behaviours, leadership, SA, adaptability, shared mental models and trust. The development of the BMS showed further interconnections between the decision-making in HMT factors and the importance of communication and mental models within the teams factor. Future work will be required to investigate how the behavioural markers for machine teammates could be applied to the design of future MASS systems to ensure systems can display these teamwork behaviours.

### **1.3.8 Chapter 8 – The application of a system-based risk management framework and social network analysis to the Maritime Autonomous Surface Ship system: Who are the decision-makers in the wider system?**

This chapter expands from the end-user perspective to bring in a sociotechnical systems perspective used to analyse the MASS system in the UK and to investigate how different actors within the system affect how MASS are operated. This chapter applied the Risk Management Framework to show how different MASS system levels interact, to investigate accountability across the system as accountability was a factor within the decision-making factors in HMT model. By including all levels from international and national committees to the end-users and equipment and environment the whole system can be seen, from those who regulate and develop standards for MASS, to those who build MASS and those who operate MASS. First, an actor map demonstrated the range of stakeholders in the UK MASS system and the hierarchical level of the system for each of these actors. From the actor map, a social network was created using the risk management framework, to show the interconnections that currently exist between the different actors in the system. A second social network was developed to explore what the MASS system may look like in the future if formal regulations were put in place for MASS and other links were added to the system. The social networks were then analysed to understand the network's dynamics, and which were the key nodes in the networks. The analysis was used to produce recommendations for each system level. It was shown that the Risk Management Framework and social network analysis can be applied to investigate accountability across a sociotechnical system to investigate how the levels of the system can be supported. The developed system recommendations showed how the factor accountability has further interconnections with other factors, such as decision support systems and task/role allocation within the decision-making factors within HMT model.

### **1.3.9 Chapter 9 – The development of a user-centred design framework for future uncrewed Maritime Autonomous Surface Ship Systems**

In this chapter, a design framework was co-developed with industry for future uncrewed MASS systems. The design framework was developed to show how a UCD approach can be used when designing novel systems even though the users and system may not yet exist. It showed how the mixed-methods approach applied in this thesis can be used to generate design and training principles

and other system recommendations to aid in the development of conceptual designs for novel systems. Firstly, the design framework was created to show how the methods used in this thesis could be applied to different stages of the design process for uncrewed MASS systems. The initial design framework was reviewed by seven industry subject matter experts to provide an initial validation for the framework. The subject matter experts' feedback on the design framework was used to create an updated design framework. The final design framework consisted of eight stages: establishing an evidence base, understanding the task, understanding the user group and domain, stakeholder analysis, concept development, the identification of Key Performance Indicators (KPIs), empirical testing and lastly, iterating for new designs. This framework could be applied to the design of novel systems to generate an evidence base for concept designs by showing how the design will support future users. Future work will be to apply this framework to design a system and to extend the framework further particularly around the development of concept designs and empirical testing of the designs.

### **1.3.10 Chapter 10 - Updating the decision-making factors in Human-Machine Teams model**

This chapter updated the decision-making factors in HMT model based on the findings from the other thesis chapters. It has shown how each of the methods in the user-centred design framework developed in Chapter 9 can be applied to explore the factors and interconnections in the initial model developed from the literature in Chapter 2. It is shown how the findings of Chapters 3 to 8 extend the initial decision-making factors in HMT model, providing further evidence for some of the existing interconnections and revealed additional interconnections between the decision-making factors. The final decision-making factors in HMT model included eight factors: decision support systems, trust, transparency, mental models, communication, task/role allocation, accountability and SA. It has shown how a mixed methods approach can be used to investigate the different decision-making factors and which methods apply to each factor in the model. Future work will be required to explore these factors to continue the development of the decision-making factors in HMT model.

### **1.3.11 Chapter 11 - Conclusions and Future Work**

This chapter summarises the findings of each chapter of this thesis relative to the objectives set in Chapter 1 and discusses the contributions to knowledge. An evaluation of the research approach is included and ideas for future research are discussed.

## **1.4 Contribution to Knowledge**

The work conducted in this thesis has contributed to the knowledge of decision-making processes in HMTs for the operation of MASS. The work demonstrated that using UCD and mixed-method

approaches are key to developing designs for highly automated and remotely operated systems such as MASS, to ensure they have considered the aspects of human-machine interactions. Often decision errors are attributed to 'human error', but the research here shows there is a need to look at how system design can influence decision-making in HMTs and that these errors are actually systemic errors. The design framework developed shows how the Human Factors methods used here can support the development of future designs to reduce the likelihood of these systemic errors.

Firstly, theoretically this research has contributed to the understanding of how decisions are made within HMT by developing a model of the factors involved in decision-making in HMTs. The initial model was developed from the decision-making in HMTs literature to show the key decision-making factors and the interactions between each of these factors. The initial validation of the developed decision-making factors in HMT model has shown its utility to real world scenarios of decision-making in HMTs when operating highly automated uncrewed systems. The application of a mixed-methods approach has been used to further investigate each of the decision-making in HMT factors showing how other factors such as mental models influence decision-making. The results were then used to update the decision-making factors in HMT model. Notably, the development of the model shows the need to consider the systemic factors involved in decision-making, to understand how system design can contribute to decision-making errors. The model could be used as a framework for validating future designs to ensure each of these factors have been considered during their design.

The methodological contributions of the research include the novel application of BMS to evaluate machine behaviours and to adapt the use of behaviour markers from assessing only human teams to applying it to HMTs. The findings showed that a BMS could be applied to an HMT as many of the human team behaviours are relevant for HMTs, although conceptually how these behaviours would be shown may differ. The BMS developed provides a framework for the design machine behaviour and evaluation of the machine behaviour during the testing and evaluation of new systems in the maritime and other domains.

This thesis has contributed practically to the development of future novel systems through the development of a design framework. The produced UCD framework has shown how the Human Factors methods used in the thesis can be applied during different stages of the early design process to develop user-centred designs for novel systems. The findings have further demonstrated that the theoretical framework of the PCM and associated methods can be applied during early design stages and that it is applicable to the maritime domain. The thesis provides practical contributions to the future design and development of uncrewed MASS systems by developing design considerations and principles, training principles, system-based recommendations and mitigation strategies that could all be applied in designing future MASS systems and the training of future operators. In addition,

system-based design recommendations have been suggested which could be applied across the levels of the sociotechnical system to support the safe design and development of MASS.

Overall, the findings in this thesis have shown how human factors methods can be applied early in the design life cycle to support the development of user-centred designs when designing novel systems. The findings have also extended the knowledge of the HMT decision-making process by identifying and investigating the key factors involved in HMT decision-making.

### **1.5 Conclusions**

In this chapter, the challenges of operating MASS uncrewed have been introduced, the aims and objectives have been described for the project, and an overview of the thesis structure and the contribution to knowledge has been outlined. The next chapter will present a review of the literature on decision-making in HMTs including maritime and other domains. The chapter will discuss the challenges in decision-making in HMTs and specifically for the operation of MASS, and explore how decision-making has previously been investigated. It also presents a systematic review to identify the key factors that influence decision-making in HMTs.

## **Chapter 2 What factors may influence decision-making in the operation of Maritime Autonomous Surface Ships? A systematic review**

### **2.1 Introduction**

This chapter aims to explore and identify the key factors that influence the decision-making process within a HMT for the operation of uncrewed MASS, especially as MASS are designed with higher levels of automation. The aim of the chapter is also to generate design considerations for MASS and identify future research avenues. A systematic review of relevant literature on decision-making in HMT was conducted to show what factors may need to be considered when designing uncrewed MASS systems to support decision-making between the human operator and the automated MASS system. A network model for decision-making in HMT was created to highlight the interconnections between these factors. The network model was then used to explore an HMT case study of an accident involving an Uncrewed Aerial Vehicle (UAV) as a comparison for MASS operations. The decision-making factors identified in the network model in this chapter will then be investigated further in each of the thesis chapters, to understand how decision-making can be supported through each of these factors.

#### **2.1.1 Decision-making and automation**

MASS using higher levels of automation are expected to be beneficial because they have the potential to reduce human workload, as some of the decision-making can be carried out autonomously (Norris, 2018). This will allow the human role to be optimised as the human can focus on decision-making where it is most needed, e.g., in abnormal situations (Mallam et al., 2020). However, automation can increase an operator's workload if it is not implemented correctly (Parasuraman, 2000). There are many examples of this within the aviation industry (Parasuraman, 2000). For example, in a fatal aviation accident at Boston's Logan airport in 1973, an aircraft struck the seawall bounding the runaway (Stanton and Marsden, 1996). One of the contributing factors to the accident was found to be cognitive strain on the crew which was caused by their automated flight director system (Stanton and Marsden, 1996). The crew's attention was on trying to interpret the information from the flight director rather than the plane's altitude, heading and airspeed which led to the accident (Stanton and Marsden, 1996).

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Automation has been defined as “the execution by machine of a function previously carried about by a human” and it has been extended to functions that humans cannot perform as accurately and reliably as machines (Parasuraman and Riley, 1997, p. 231). This differs from autonomy which has been defined as “the ability of an engineering system to make its own decisions about its actions while performing different tasks, without the need for the involvement of an exogenous system or operator” (Vagia et al., 2016, p. 191; Albus and Antsaklis, 1998). There are various taxonomies of levels of automation for a system, which describe the level of human involvement in the system operation (Endsley and Kaber, 1999; Sheridan and Verplank, 1978). As the ships gain higher levels of autonomy due to more advanced technology becoming available, the role of the human operators changes from being an active role in the ship functions to a monitoring role either onboard the vessel or from a Remote Control Centre (RCC) (International Maritime Organisation, 2021).

However, it is anticipated that the operation of MASS will lead to some familiar Human Factors challenges as seen in other domains as the role of the human operator changes from an active to a more supervisory role (Mallam et al., 2020). Changing the role from a human in the loop (HITL), where the human operator inputs commands and makes decisions whilst the system carries out automated tasks (Mallam et al., 2020; Nahavandi, 2017), to a human on the loop system (HOTL) whereby the human is monitoring an automated system may lead to potential problems due to humans being notoriously poor at monitoring tasks (Mallam et al., 2020; Nahavandi, 2017; Parasuraman and Riley, 1997). Poor monitoring of the automated systems may be due to an operator’s overreliance in the system which can cause decision errors, leading to incidents and accidents (Parasuraman and Riley, 1997). Active monitoring of ship performance, weather conditions, engine performance and ship communication have been suggested as areas for MASS to keep human operators ‘in the loop’, so problems can be identified early (Porathe et al., 2020). However, if a ship has no issues and is in open water for long periods, there is a risk that the human monitoring will become bored and a passive monitor (Porathe et al., 2020). This is a problem as they will become ‘out-of-the-loop’ and require time to get back in the loop, which could be crucial in an emergency (Porathe et al., 2020).

Despite this automation has been heralded as a technology that can help overcome human error, such as errors induced by fatigue, limited attention span and information overload (Ahvenjärvi, 2016; Hoem, 2020). These “human errors” are not necessarily the cause of the incidents or accidents but are due to design, planning and procedure flaws in the system that result in these system errors (Hoem, 2020). Replacing the human with automation does not remove these errors completely, it just changes the nature of them and changes where these errors occur as there will still be a human

involved in the system (Ahvenjärvi, 2016; Hoem, 2020). This has been seen in a study of collisions between attendant vessels and offshore facilities in the North Sea, contributing factors to these collisions were the inadequate design of interfaces, communication failure and lack of sufficient training for the automation (Sandhåland et al., 2015). These accidents show the importance of considering the design of decision support systems to minimise the likelihood of these system errors occurring.

### **2.1.2 Challenges in MASS operation**

A key human factors challenge in similar highly automated domains such as ,uncrewed aircraft systems is that operators have increased levels of boredom due to the increased monitoring tasks, as well as problems during handovers leading to accidents (Wahlström et al., 2015). Handover issues during emergencies are also a problem seen in highly automated vehicles, as drivers become ‘out-of-the-loop’ when they are no longer actively involved in the driving task (Large et al., 2019). Humans may not always be aware of an automated system’s limitations and therefore will not know when to take back control from the system, as well as having potentially a short window to take back control (Norman, 1990; Stanton et al., 1997). Therefore, it is likely that MASS operators may find similar issues relating to maintaining their vigilance.

It has also been found that there are human factors challenges in other remote monitoring domains such as aviation and it has been suggested that similar challenges may be seen in MASS operation. An example of one of these challenges in the aviation domain, that operators had a general lack of feel for the aircraft, due to the missing proprioceptive cues as the pilots can no longer feel shifts in altitude and changes in engine vibrations, which can be an issue when diagnosing system faults as it leads to a loss of SA (Wahlström et al., 2015). Similarly, it has been suggested that a lack of ‘ship sense’ (the knowledge that is gained by using the navigator’s senses e.g., the feeling of the ship’s movement and the visibility from the outside environment) due to MASS operators no longer being on board will also be a challenge for operating MASS safely (Porathe et al., 2014; Yoshida et al., 2020). Although further investigation will be needed to explore how SA changes when operating MASS as it could increase or decrease SA depending on the system’s design.

Such challenges may also be present in MASS operations of the future. For instance, one approach for MASS is to follow a pre-programmed route. If the ship goes outside of a safety margin on either side of this route, then an operator at a RCC may have to take over or monitor the autonomous system as it selects a new path to navigate (Porathe et al., 2020). Operators may also need to monitor the ship’s systems to check for any faults and assess the severity of any faults found, then

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make decisions about whether the ship may need to divert off route for repairs (Man et al., 2016). It has also been suggested that decision-making will be more difficult in a RCC as it will potentially take longer for decisions to be made as operators get back into the loop (Porathe et al., 2014) as they will need to quickly understand and assess the situation, which may be difficult due to the lack of proximity between the operator and the uncrewed ship and the high levels of automation (Endsley and Kiris, 1995; Onnasch et al., 2014; Porathe et al., 2014). It has already been identified that decision-making for all the different functions of a RCC such as, monitoring ship health and status, monitoring and updating the ship's route is an important requirement in the RCC (Man et al., 2016; Porathe et al., 2014). This further shows the importance of considering the HMT decision-making processes in the design of MASS decision support systems (Man et al., 2016; Porathe et al., 2014).

There is also a potential issue of having an operator monitor more than one uncrewed vehicle as current systems and human-machine interfaces are already struggling to support the monitoring of a single-vehicle (Cook and Smallman, 2013). Similarly, Wahlström et al. (2015) agrees that there is a potential to overload an operator with the task of monitoring more than one vessel, due to the large number of sensors that would be gathering information on an autonomous ship. It is suggested that due to the operator not being onboard, more information about the ship will have to be given to the operator, which could also contribute to the operator being overloaded (Wahlström et al., 2015). It has been suggested that the cognitive demand is expected to be higher for RCCs, so it may be an important consideration in their design (Dreyer and Oltedal, 2019). Another factor that may affect the workload of the remote operator is the usability of the automated control systems (Karvonen and Martio, 2019). If the usability of the system is poor then operators may become 'out-the-loop' and may miss important safety information (Karvonen and Martio, 2019).

A UAV case study has been selected as the operation of UAVs shares similarities with the operation of MASS and because MASS are a less operationally established technology and at the time of writing there were MASS accident case studies were not available in the unclassified mainstream literature. For example, the similarities in their operation are:

- Both UAVs and MASS are operated from RCCs and therefore they will be reliant on predominantly digital information from sensors (Ahvenjärvi, 2016; Gregorio et al., 2021; Man et al., 2018a; Skjervold, 2018)
- There is a lack of proximity between the operator and uncrewed vehicle (Gregorio et al., 2021; Hobbs and Lyall, 2016; Karvonen and Martio, 2019; Pietrzykowski et al., 2019)

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- The maritime and aviation domains are both safety-critical, e.g., operators are responsible for the safety of the vehicle and handling system faults and failures (Boll et al., 2020; de Vries, 2017; Plant and Stanton, 2014a)
- The operators' roles are changing to a supervisor monitoring highly automated systems, so their types of tasks are cognitively similar as they will be checking displays and will make few system inputs, whilst more of the decision-making is carried out by the system (Man et al., 2018b; Skjervold, 2018)
- Higher levels of automation are being used so that less operators are needed and operators can operator multiple uncrewed vehicles or taking on other secondary tasks (Mackinnon et al., 2015; Skjervold, 2018).

Due to the similarities in their operation, it is likely that comparable issues will be seen in both domains. For example, operators may transition to a supervisory role which can lead to them becoming out of the loop and no longer being aware of what the automated system is doing (Goodrich and Cummings, 2015; Karvonen and Martio, 2019; Man et al., 2018b). Another issue which may be found in the operation of UAVs and MASS is that the operator might become cognitively overloaded if vast amounts of data from the automated system are displayed to them or underloaded in long periods of monitoring (Deng et al., 2020; Kerr et al., 2019; Man et al., 2014; Wahlström et al., 2015). It has been found in the operation of UAVs that operators have limited SA due to no longer having the same sensory cues as they would onboard the aircraft, which has also been suggested may be the case for MASS (Hobbs and Lyall, 2016; Hunter et al., 2017; Karvonen and Martio, 2019). However, there are differences between their operation such as navigation in the aviation domain is in three dimensions versus the maritime domain which is only in two dimensions (Praetorius et al., 2012). Another difference between the two domains is that the vehicles in the aviation domain are travelling at much higher speeds than in the maritime domain, which means that operators of UAVs have shorter times in which to make decisions (Praetorius et al., 2012).

However, in addition to the general challenges of using high levels of automation there are other challenges specific to MASS which will need to be further investigated. MASS operators may have more time to make decisions, but they will also be responsible for additional tasks such as collision avoidance, whereas in aviation this is done by air traffic control who help control the flow of aircraft (Praetorius et al., 2012). Another challenge is the complexity of the maritime environmental conditions in which the operator is navigating, as these conditions are much more dynamic and complex (Mikkers and Henriqson, 2012). There are also the differences in how the operator will view the world, changing from large windows to potentially separate smaller windows which could affect

their ability to scan the environment as easily and interpret information, which may be an issue for decision-making as operators are more reliant on visual information. These differences may limit the transferability of using an aviation case study when trying to understand the implications of operating MASS, however, as their operations are similar there may be lessons that can be learnt from operating UAVs for MASS.

## 2.2 Method: Understanding Decision-Making in Human-Machine Teaming

### 2.2.1 Search Methods and Source Selection

Four comprehensive searches were conducted (in October 2020) to explore decision-making in human autonomous machine teams (see Table 2 for the search terms used for decision-making in human autonomous machine teams) using Google Scholar, Research Gate, Scopus, and Web of Science databases. Due to the number of the search results, searches were limited to 50 articles from Google Scholar and Research Gate and were sorted by relevance to try to ensure key literature was covered. A further search was also carried out for accountability in decision-making in HMT (in November 2020) as it is an important consideration in the application of MASS, especially at higher levels of autonomy due to the automated system having some decision-making power. A fifth search was then conducted (see Table 2.1), to investigate accountability in decision-making in a HMT this search was limited to ten articles from Google Scholar and Research Gate as Scopus and Web of Science searches only gave six and four articles respectively.

The articles were selected using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) selection process (Moher et al., 2009), shown in Figure 2.1 and was used to reduce the initial total of articles from 932 articles to 47 articles. Articles relating to machine learning and decision algorithms were excluded, as they related to the technical development of decision-making software and were not the focus of this research. Articles which solely discussed the design of interfaces were also excluded as they did not specifically focus on the HMT decision-making process. Due to the specific nature of the search terms used, literature on the effects of automation on the human decision-making process has also been included in the review (18 articles).

Table 2.1 - Search terms used, and number of articles found for each database.

Search Terms	Google Scholar	Scopus	Web of Science	Research Gate	Totals

('decision' OR 'decision-making') AND ('autonomous') AND ('human-machine')	50	165	93	50	358
('decision' OR 'decision-making') AND ('autonomous') AND ('maritime') AND ('human-machine')	50	2	0	6	58
('decision' OR 'decision-making') AND ('autonomous') AND ('military') AND ('human-machine')	50	14	5	38	107
('decision' OR 'decision-making') AND ('theory' OR 'theories' OR 'method' OR 'methods' OR 'model' OR 'models') AND ('human-machine')	50	145	134	50	379
('decision' OR 'decision-making') AND ('human-machine') AND ('accountability')	10	6	4	10	30
Totals	210	332	236	154	932

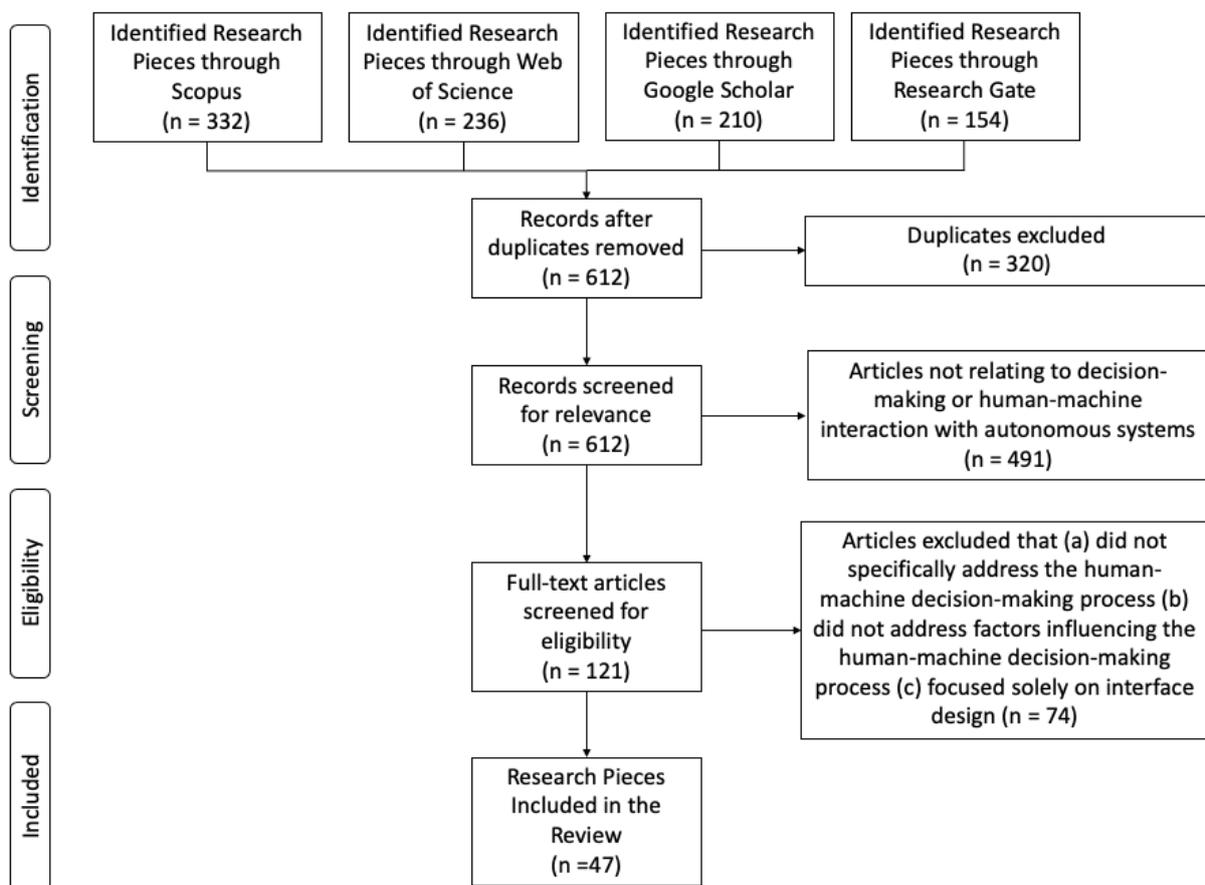


Figure 2.1 - Filtering process used to find relevant articles for the review.

### **2.2.2 Theme Elicitation: Identification of Themes in Decision-making in Human-Machine Teaming**

Following the selection of the articles, a thematic analysis of HMT literature was conducted using a grounded theory approach (Braun and Clarke, 2006). Themes were generated by iteratively reviewing the literature, searching for themes within the data, and reviewing and refining the themes generated from the literature (Braun and Clarke, 2006). This approach was chosen as past literature reviews (e.g., (Foster et al., 2019; Rafferty et al., 2010; Sanderson et al., 2020) have successfully used the grounded theory approach to elicit core themes from bodies of literature. Seven themes were produced using this approach: decision support systems (DSS), trust, transparency, task/role allocation, teams, accountability, and SA. To see the themes identified in each paper included in the review see Appendix A. As the coding of themes can be subjective inter-rater reliability was conducted to assess the reliability of the coding. Two raters were given a coding scheme of the seven themes identified and asked to code text segments from 16 of the 65 papers included in the review. An average percentage agreement of 85% was found for the coded themes, which was over the 80% percentage agreement that has been used in the literature as an acceptable level of percentage agreement between raters (Jentsch, 2005; Plant and Stanton, 2013b).

### **2.2.3 Identification of Interconnections between the 7 themes of Decision-making in Human-Machine Teams**

The HMT articles were reviewed iteratively again to explore any connections between the seven themes identified and any interconnections found were recorded (including notes on directionality). The interconnections found included where themes were discussed in reference to other themes and where the effect of themes on other themes had been investigated. To assess the reliability of the interconnections coding an inter-rater reliability analysis was conducted with two raters who were given text segments of 15 out of the 71 connections included in the Network Model. A moderate percentage agreement was found, which resulted in a discussion between the raters where the coding scheme was refined, and a consensus was agreed to reach a percentage agreement of 80%.

## 2.3 Results

### 2.3.1 Interconnections between the 7 themes of Decision-making in Human-Machine Teams

The results of the interconnections between the themes are presented in a Network Model in Figure 2.2. It shows that there are many interconnections between these themes, the highest being between DSS and SA. The DSS used may influence the human’s ability to maintain their SA which as discussed previously will be an important factor in their ability to make high-quality decisions (Ahvenjärvi, 2016; Endsley, 1995; Mackinnon et al., 2015). Figure 2.2 also shows that the design of the DSS will also have an effect on how the tasks or roles are allocated within the HMT, which may influence the safety and performance of the HMT (Miller and Parasuraman, 2007; Parasuraman et al., 2007). Similarly, it shows the type and design of the DSS will also influence how accountability is viewed within the HMT, which may influence the HMT decision-making process (Benzmüller and Lomfeld, 2020; de Laat, 2017; Lemieux and Dang, 2013; Loh and Loh Sombetzki, 2017). The connections between trust and DSSs describe how the design and reliability of the DSS may affect a user’s level of trust in it and how their level of trust may affect their use of a DSS (Barnes et al., 2017a; Matthews et al., 2016; Parasuraman and Manzey, 2010; Sadler et al., 2016).

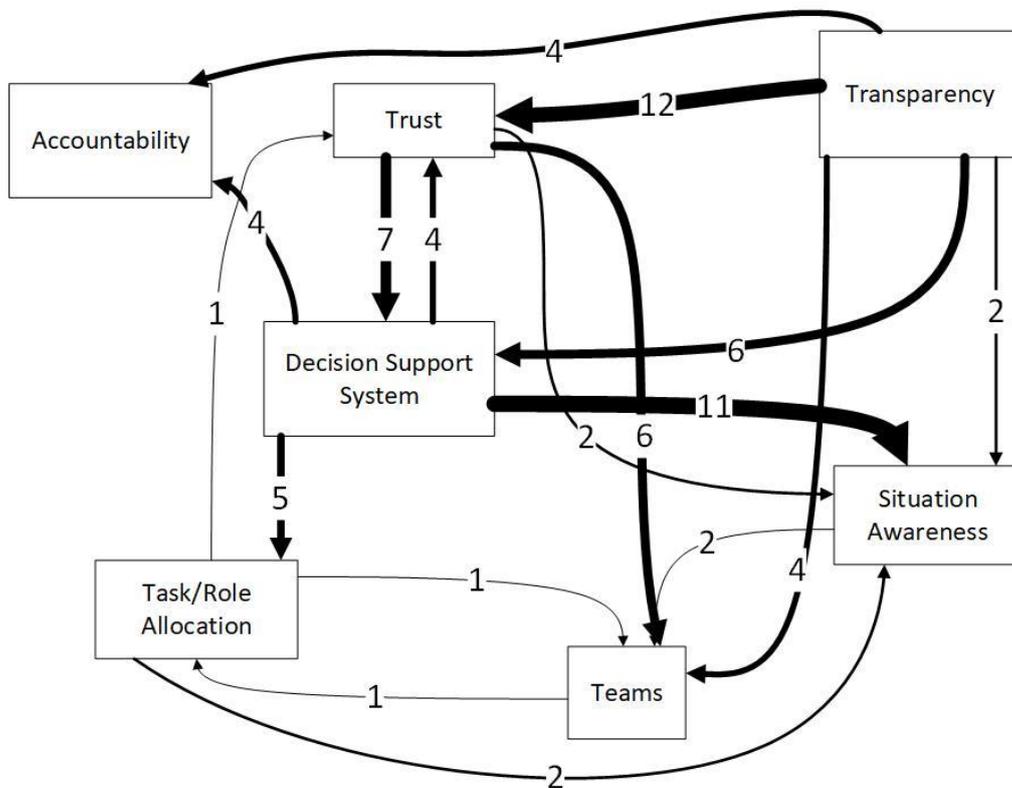


Figure 2.2 – Decision-Making in HMT model showing the interconnections between the themes and the number of papers found for each interconnection.

The relationship between trust and transparency in a HMT can be seen in the Network Model. The level of transparency of an automated system will change the human's trust in the system as the transparency chosen will affect their knowledge of the system's processes (Fleischmann and Wallace, 2005; Panganiban et al., 2019). It was also found that the individual differences in trust could potentially be used to configure a level of transparency to ensure that the human has an appropriate level of trust (Matthews et al., 2020; Sadler et al., 2016). The transparency of DSSs has been investigated to find what the effect is on trust, SA and overall system performance (Barnes et al., 2017a; Sadler et al., 2016; Tulli et al., 2019). Figure 2.2 shows the relationship between transparency and accountability, that accountability could be achieved by increasing the system's transparency to give human's a greater understanding of the system's decision-making process (Benzmüller and Lomfeld, 2020; de Laat, 2017). It was found that both trust in an automated system and the transparency of that system can influence teamwork, so it will be important to consider these influences on the HMT decision-making process (Ishowo-Oloko et al., 2019).

### **2.3.2 7 Themes in Human-machine Teaming Literature**

#### **2.3.2.1 Theme 1: Decision Support System**

Decision Support Systems (DSS) are used in complex environments to support human decision-making (Parasuraman and Manzey, 2010). DSSs have a wide range of uses, they have been used to alert pilots to mid-air collisions (Parasuraman and Manzey, 2010), enhance military tactical decision-making (Morrison et al., 1996) and support emergency workers' decision-making in a disaster. There are two main functions of DSS to either alert the human (e.g., to a system failure) or to give them a recommendation (e.g., recommendations on proposed routes) (Parasuraman and Manzey, 2010).

Various approaches have been used to design DSSs such as participatory design where users are aid the design process (McNeish and Maguire, 2019; Smith et al., 2020; Spinuzzi, 2005) and scenario-based design (Carroll, 1997), where a user interaction scenario is used to develop a design (Smith et al., 2020). These approaches could be used for the design of MASS DSSs to ensure that a user-centred design approach is used so that the systems have been designed to support operators' decision-making. Cognitive Task Analysis (CTA) has also been applied in the design of DSSs (O'Hare et al., 1998) to model the components of a task and the thought processes used to carry out that task, the DSS can then be designed to support these processes (O'Hare et al., 1998; Smith et al., 2020). Knisely et al. (2020) used CTA to decompose tasks in a monitoring control room and investigate human performance in control rooms, which suggests that CTA may also be applicable to investigate RCCs as operators of MASS will be expected to perform similar monitoring tasks. It was

recommended that supervisory tasks should avoid having peaks in cognitive workload and try to remain at a constant level of workload, which may also be an important consideration for MASS DSSs (Knisely et al., 2020). Other task analysis techniques such as Hierarchical Task Analysis (HTA) (Stanton, 2006) have been used to identify tasks and decompose them for a collision-avoidance system for MASS operation (Ramos et al., 2019). This suggests that HTA could be used to aid the design of other MASS DSSs and could be used to further explore how other tasks of operators at RCCs could be supported (Ramos et al., 2019).

The use of DSSs may affect how HMTs make decisions, so it is important to consider their design as the role of the human changes, as a result of the automation (Cook and Smallman, 2013; Mallam et al., 2020; Voshell et al., 2016). The DSS will need to support the human in supervising their machine teammate and in the management of the HMT by creating a shared state of knowledge (Madni and Madni, 2018; Voshell et al., 2016). Designing effective DSSs has been suggested to minimise oversight and error in HMTs, as shared decision-making will greatly affect the performance of the HMT and it will be necessary to investigate how DSSs could be designed to support shared decision-making between the operator and the MASS' automated system (Ahvenjärvi, 2016; Madni and Madni, 2018; Norris, 2018). DSSs can also be used to support communication in a HMT and help the team to develop shared SA by presenting information to the human in an appropriate way, it will be necessary to investigate how this information should be presented for MASS operators to develop that shared SA (Schaefer et al., 2017). Limited SA has been highlighted as one of the main issues with operators operating MASS from RCC, so DSSs for RCC operators must provide them with the necessary SA to be able to make high-quality decisions (Wahlström et al., 2015). Another function of DSSs is to provide transparency to the human about the processes of their autonomous teammate, which will affect their level of trust in the system (Barnes et al., 2017a; Panganiban et al., 2019; Westin et al., 2016).

### **2.3.2.2 Theme 2: Trust**

A human's trust in an automated system has been defined as a function of predictability, dependability, and faith in that system (Lee and Moray, 1992). However, there are many different definitions of trust (see Lee and See (2004); Hoff and Bashir, 2015). Overreliance and under reliance are potential issues in a HMT, if the operator overtrusts the system it could lead to accidents if the system is not being monitored adequately or the operator may reject the capabilities of the system (Karvonen and Martio, 2019; Lee and See, 2004; Parasuraman and Riley, 1997). This will be important as the main role of MASS operators at higher levels of automation will be to monitor the system effectively (Dybvik et al., 2020; Hoem et al., 2018; Ramos et al., 2019; Størkersen, 2021).

## Chapter 2

Mallam et al. (2020) interviewed maritime subject matter experts on the potential impact of autonomous systems and trust was found to be one of the dominant themes. If an agent lacks trust, they are less likely to rely on their autonomous teammate (Boy, 2017; Hoc, 2000; Karvonen and Martio, 2019; Millot and Pacaux-Lemoine, 2013). The system's ability to communicate intent then becomes important, as a human's trust will depend on whether they believe the system's goals are in line with their own goal (Matthews et al., 2020; Schaefer et al., 2017). Therefore, it is important to consider how trust is built in HMTs for the operation of MASS to help support cooperation and appropriate reliance between the operator and MASS (Barnes et al., 2017a; Matthews et al., 2016; McDermott et al., 2017; Millot and Pacaux-Lemoine, 2013). It has been found that Adaptive Automation (AA) can be used to reduce overtrust and increase the detection of system failures, by shifting between manual and automated control depending on the operator and situation, which may be appropriate in the design of MASS (Lee and See, 2004).

Vorm and Miller (2020) investigated factors that influence trust in an autonomous system. It was found that the participants thought understanding the variables considered in recommendations and their weightings were important, suggesting system transparency can influence trust (Vorm and Miller, 2020). In contrast, in Lyons et al's (2019) study transparency was not found to be a prominent factor. Instead, it was found that reliability, predictability and task support were important factors in the participant's trust. However, this may have been due to the type of technologies being discussed as participants were asked about intelligent technologies not necessarily autonomous systems, so these findings may not be applicable to MASS.

Hoff and Bashir (2015) presented a three-level model of trust in automation from the analysis of a systematic review, these levels were: dispositional trust, situational trust and learned trust. Dispositional trust represents an individual's propensity to trust, it has been suggested that high levels of dispositional trust led to higher levels of trust in reliable systems (Hoff and Bashir, 2015; Matthews et al., 2020; Nahavandi, 2017). It has been suggested that initial expectations and trust are formed from the operator's own mental models (Matthews et al., 2020; Warren and Hillas, 2020). Although, there is a potential difficulty in forming accurate mental models, as operators may not have a detailed understanding of the system or have experience using it (Matthews et al., 2020; Warren and Hillas, 2020). It has been found that lower levels of self-confidence and can lead to higher levels of trust, which can often be found in novices who are more likely to rely on the automation (Hoff and Bashir, 2015; Lee and Moray, 1994; Lee and See, 2004).

The second level, situational trust depends on the type and complexity of the automated system, it has been found that there can be a perception bias due to external situational factors, such as the

reliability of other automated systems in use and the level of risk in the environment (Hoff and Bashir, 2015). The third level learned trust is influenced by the operator's prior knowledge of the system and their experience using that automated system (Hoff and Bashir, 2015; Mallam et al., 2020). It has been shown that trust can be influenced and reduce complacency by training operators about a DSS's actual reliability (Hoff and Bashir, 2015). The reliability of the automated system, in the form of false alarms (the system incorrectly alerts the operator to an issue) and misses (when the system fails to alert the operator) can reduce trust (Hoff and Bashir, 2015; Lee and Moray, 1992). As completely reliable automation is unachievable it will be necessary to consider how the system is designed to give an appropriate level of trust, operators could be shown the processes of the automated system in an interpretable way or provided with intermediate results to verify them (Lee and See, 2004).

### **2.3.2.3 Theme 3: Transparency**

The transparency of an automated system describes the degree to which the human is aware of what the system's processes are and how they work. Transparency has been shown to improve task performance and lead to appropriate trust, by providing accurate information on the reliability of the system (Hoff and Bashir, 2015). However, how this reliability information is displayed can have different effects on HMT performance (Hoff and Bashir, 2015). Integrated displays showing task and reliability information have been found to be relied on more appropriately and to improve task efficiency (Neyedli et al., 2011). In this case, the design of a combat identification system was investigated and it was found that integrating information such as target identity (different colours for targets and non-targets) and system reliability (using a pie chart or mesh displays) showed improvements in the participants' task efficiency and appropriate reliance (Neyedli et al., 2011). Oduor and Wiebe (2008) found that the participant's perceived trust was rated lower when the system's decision algorithm was hidden from them. It was also found that the transparency method (textual or graphical) used had more of an effect on trust (Oduor and Wiebe, 2008).

Many autonomous systems hide their decision-making processes from the human operator due to their complexity, making it difficult for them to be interpretable (Seeber et al., 2019; Stensson and Jansson, 2014). Giving operators more information about a system's decision-making processes, could allow operators to form more accurate mental models of their autonomous teammates and lead to higher levels of trust (Mallam et al., 2020; Matthews et al., 2016). Allowing an operator to evaluate the automated system, by making them aware of its assumptions could lead to higher quality decisions in the HMT (Dreyer and Oltedal, 2019; Fleischmann and Wallace, 2005; Mallam et al., 2020).

It has been suggested that transparency is required for a HMT relationship to give each teammate a shared understanding of the task, objectives and progress (Barnes et al., 2017a; Barnes et al., 2017b; Johnson et al., 2014; McDermott et al., 2017). The Situation awareness-based Agent Transparency (SAT) model developed by Chen et al. (2014) describes supporting the operator's SA using three levels: level one what's happening and what the agent is trying to, level two why the agent does it and level 3 SA what the operator should expect. It was found that levels one and two can improve subjective trust and SA in a HMT (Barnes et al., 2017a). However, including level three information did not improve trust suggesting further investigation is required (Barnes et al., 2017a).

The effect of transparency on trust and reliance has been investigated in a HITL scenario of pilots using an autonomous constrained flight planner (Sadler et al., 2016). It was found that the pilot's trust increased with the transparency of the flight planner, when the pilots' were given risk evaluations and the system's reasoning (Sadler et al., 2016). However, it was also found that as the level of transparency increased the pilots were less likely to accept the system's recommendations (Sadler et al., 2016). This suggests that increasing transparency for the HITL scenario allowed operators to make informed decisions, suggesting that transparency will also be important for HOTL system designs (Sadler et al., 2016). In contrast, Tulli et al. (2019) found no significant effect of transparency on cooperation and trust in HMTs, it was found that the system's strategy had the greatest effect on the cooperation rate and trust in the HMT.

The MUFASA project investigated automation decision acceptance and the performance for air traffic control DSSs (SESAR Joint Undertaking, 2013). It was found that controllers rejected 25% of cases even though they agreed with their strategies and they had difficulties in understanding the system's strategies (Westin et al., 2016). The effect of transparency on DSSs for air traffic controllers was investigated to understand why the recommendations had been rejected in the MUFASA project (Westin et al., 2016). Although one DSS was perceived as being more transparent than the other, transparency of the DSSs did not affect the controller's acceptance rate, this suggests other factors may be involved (Westin et al., 2016).

It has been shown that humans are less likely to cooperate with their teammate if they know they are a robot (Ishowo-Oloko et al., 2019). However, robots can elicit better cooperation than human-human teams, if the human teammate is incorrectly informed that their teammate is a human and not a robot (Ishowo-Oloko et al., 2019). Although these findings may not apply to the operation of MASS, as the human will be aware they are working with an automated system, it does suggest that further investigation is required to find out why better cooperation was found in that case.

#### 2.3.2.4 Theme 4: Teams

Using a system with a higher level of autonomy that can make its own decisions, means that teamwork becomes important. The human and the automated system must be able to work together to achieve the overall system goal. The decision-making will be shared between them at the higher levels of autonomy, so it is important to understand what might affect the HMT's ability to make decisions, how teamwork can be supported and determine how HMTs can be investigated.

Teamwork is supported by a shared mental model (Bruemmer et al., 2002). If the mental model is complementary, each team member has the information that they need to carry out their task. Team members will need to understand "who" holds "what" information (Boy, 2017; Bruemmer et al., 2002). It has been shown that team members in high workload environments perform better and communicate more effectively when they share similar knowledge structures (Boy, 2017).

Transparency influences teamwork in HMTs, by understanding a teammate's intention it could mean that each teammate could better anticipate where their teammates might need support, which could increase team performance (Johnson et al., 2014; Lyons et al., 2019; Schaefer et al., 2017).

Tossell et al. (2020) suggested various guidelines for representing military tasks for HMT research and that it is necessary to prioritise the level and type of fidelity that is appropriate for the research objective. The Wizard of Oz technique was suggested as a way of maintaining fidelity whilst the technology is still in development, the technique involves a human playing the role of the computer in a simulated human-computer interaction (Bartneck and Forlizzi, 2004; Steinfeld et al., 2009). The application of this technique then allows fidelity to be maintained even though the technology is not advanced enough to be used at that stage (Bartneck and Forlizzi, 2004; Steinfeld et al., 2009).

Simulating smoke and other environmental factors to create a sense of danger can also be used to increase fidelity when representing a military task (Tossell et al., 2020). The level of fidelity used in HMT research is important as it defines the degree to which a simulation replicates reality, a higher fidelity system is a closer representation of the real world (Tossell et al., 2020). It will be important to consider the fidelity when researching HMT for the operation of MASS.

For instance, Walliser et al., (2019) used the Wizard of Oz technique to explore the impact that team structure and team-building have on the HMT. It was found that framing the relationship as a team rather than a tool-like relationship, gave improved subjective ratings of cohesion, trust and interdependence and participants were more likely to adapt roles during the scenario to support teamwork (Walliser et al., 2019). However, it did not show an improvement in team performance

(Walliser et al., 2019). Instead, formal team-building exercises (e.g., clarifying roles and goals) have been found to improve team performance and communication (Walliser et al., 2019).

Chung et al. (2009) developed a framework, based on Rasmussen's (1974) decision ladder, for team communication in nuclear power control rooms. It showed where communication errors may occur in the control room and may be applicable to investigating communication in MASS HMTs (Chung et al., 2009). Effective communication will be important so that both the human and the automated system have appropriate task-relevant information available to them to be able to make decisions (Matthews et al., 2016). It is also important that information is provided that supports team cohesion and coordination, to help build team resilience as each member can then step in to support if required (Matthews et al., 2016). It has been found that the team type (independent or dependent) has an effect on trust and that those who were dependent (shared tasks with their autonomous teammate) reported higher levels of trust (Panganiban et al., 2019). It was shown that individuals are inclined to team with an autonomous teammate when carrying out a military task, but this may not be transferrable to real-world military scenarios due to the simplicity of the scenario (Panganiban et al., 2019).

### **2.3.2.5 Theme 5: Task/Role allocation**

The divisions of tasks and roles will have to change at higher levels of automation. The introduction of higher levels of automation does not mean that tasks will just be shifted from human to automated systems, it also means that the nature of the tasks may change and new tasks may be added or other tasks removed (Parasuraman et al., 2007). It has been proposed that the division of tasks between the human and automated system describes the nature of the cooperation (Simmler and Frischknecht, 2020). The coordination of these new tasks and roles will also then be crucial to the functioning of the HMT (Parasuraman et al., 2007). Human supervisors of these systems will need an understanding of the divisions of tasks and roles, to delegate tasks to the automated system and understand their responsibilities (Parasuraman et al., 2007). The addition of facilitation in the HMT changes it to one of cooperation as each teammate tries to manage the interference to support the team goal (Hoc, 2000; Navarro, 2017). It has been suggested that using a Common Frame of Reference (COFOR; Hoc 2001), creating a shared knowledge, belief and representation structure between two agents, similar to shared SA (Endsley and Jones, 1997) could allow more effective cooperation (Milot and Pacaux-Lemoine, 2013).

The task allocation in a HMT and for MASS may have human performance consequences on workload, SA, complacency and skill degradation (Hoc, 2000; Parasuraman et al., 2000). It has been

found that using automation to highlight or integrate information can be useful in reducing workload (Parasuraman et al., 2000). However, if automated systems are difficult to initiate and engage, an operator's cognitive workload is increased (Karvonen and Martio, 2019; Parasuraman et al., 2000). The effect of automation on SA will be discussed in greater detail in section 3.1.7, it is important to note that automating decision-making functions can reduce an operator's SA (Parasuraman et al., 2000). It has been found that humans are less aware of decisions made by an automated system, than when the human is in control of the task (Miller and Parasuraman, 2007). It has been suggested that for high-risk environments in future command and control systems, decision automation should be set to a moderate level allowing the human operator to still be involved in the decision-making process and retain some level of control (Parasuraman et al., 2007).

It has been shown that adaptive task allocation, where the task allocation is dynamic and moves between the human operator and the automated system can improve monitoring performance (Parasuraman et al., 1997) could be appropriate during periods of low or moderate workload so the operator would not be overloaded due to the handover of control (Parasuraman et al., 1997). However, the implementation would need to be considered to ensure that the intentions of the system are clear to the operator and that the task is appropriate for human control (Parasuraman et al., 1997). AA can also be used to reduce operator workload or used to increase their SA when the former is detected to be too high or the latter is too low (Parasuraman and Wickens, 2008). It has been suggested that the human could be in charge of the AA but that may increase their workload and lose the benefit of using the AA, so it would be important to consider these issues if AA is used for MASS (Parasuraman and Wickens, 2008).

Introducing flexibility in team roles poses a challenge for HMTs because any change in role must be communicated to the other agents. All agents must maintain an awareness of workload and task performance and be capable of adapting their behaviour when required (Bruemmer et al., 2002). However, this introduces the potential for a new class of errors due to handing over the new roles or tasks between the human and automated system. As machines become more involved in higher-level decision-making processing, it may make management structures and responsibility more difficult to define, as the human will not be in full control (Seeber et al., 2019). Another challenge in allocating roles in a HMT is avoiding conflict situations. A conflict situation may arise when the automated system has the authority to carry out a specific action but due to failure or error, the human agent may be held responsible/accountable even though they were not directly involved in the action (Voshell et al., 2016).

### 2.3.2.6 Theme 6: Accountability

Accountability is a challenge in HMTs as responsibility is divided between the human and an automated system (Boy, 2017). If the human operator does not fully understand an automated system and they are unable to explain its processes, it raises the question of if they can be held accountable for the behaviour of the system (Simmler and Frischknecht, 2020; Taylor and De Leeuw, 2020). Similarly, Benzmüller and Bertram Lomfeld (2020) discussed how accountability could be determined if the system's decision-making process is hidden from the system users. It was suggested that these systems need to be made interpretable and communicate their reasoning for a decision to the human, to help with the issue of accountability (Benzmüller and Lomfeld, 2020). There are also concerns about accountability in the use of military automated systems. For instance, if a defence analyst agrees with a recommendation from an automated system and something goes wrong, the analyst may be held accountable for that decision even though they may not have had a full understanding of the decision behind the recommendation (Warren and Hillas, 2020). By increasing the transparency of these decision-making processes of highly automated systems it may be possible to determine levels of accountability when there is an incident or accident (Benzmüller and Lomfeld, 2020; Taylor and De Leeuw, 2020).

In degrees two and three of autonomy of MASS (see section 2.2) where the ship's system is remote controlled and human operators control the decision-making process. In degree four of autonomy, the ship's system is fully autonomous which introduces diffused accountability as multiple people are responsible for the system's design and its operation (Loh and Loh Sombetzki, 2017). However, de Laat (2017) also raises concerns about increasing the transparency in decision-making algorithms such as potential data leaks, people working around the decision-making algorithms and the decision-making algorithms may not be easily understood even if they are transparent. Although de Laat (2017) refers to decision-making algorithms specifically, these points are transferable to autonomous systems, as operators could potentially be unaware of how these systems make decisions.

It has been suggested that recording decision-making and actions in cognitive systems could be a way to establish who made the decision and therefore engineer accountable decision-making in the system (Lemieux and Dang, 2013). Whilst this could help establish accountability after an incident or accident by tracking which agents made the decisions, it does not address how the decision-making processes of the agents involved in the HMT will change with the introduction of a highly automated teammate. McCarthy et al. (1997) developed a framework to investigate organisation accountability in high consequence systems, as often failures in organisational processes leave operators with

conflicting goals. McCarthy et al. (1997) argued that it is necessary to understand the relationships between accountability, work practice and artefacts within a system to be able to infer the requirements for the design of the high-consequence systems. McCarthy et al. (1997) also discussed task and role allocation within a system, that operators need to have the necessary level of control within the system to infer accountability. However, as the decision-making may be shared between the human and the autonomous system for various tasks this would still be an issue, as accountability might not be as easily inferred from the task or role allocation (Boy, 2017).

### **2.3.2.7 Theme 7: Situational Awareness**

One key Human Factors challenge for the operation of MASS is that the operators are still able to maintain SA (Endsley, 1995) despite no longer being present aboard the ship. SA plays an important role in human decision-making in dynamic situations as it describes the decision maker's perception of the state of the environment (Endsley, 1995). Endsley (1995) defined three levels of SA, perception of elements in the environment (level 1), this could be the operator recognising the ship's location and other nearby ships' locations. Comprehension of the current situation (level 2), the ship may be on a collision course with another ship, and the projection of future status (level 3) (Endsley, 1995).

From a design point of view the information displayed by a DSS and how that information is displayed will affect an operator's ability to perceive and understand the situation, therefore affect the quality of their decisions (Endsley and Kiris, 1995; Endsley, 1995; Parasuraman et al., 2008). It has been proposed that an operator should have the same information available as they would have onboard a ship (Karvonen and Martio, 2019; Ramos et al., 2019). Reduced SA for MASS may be due to a lack of sense of the ship rocking or other environmental conditions, affecting their ability to steer the ship in poor weather conditions, a lack of vehicle sense has already been found in aviation when using remote operation (Ramos et al., 2019; Wahlström et al., 2015). This has safety implications because a lack of SA could increase the likelihood of accidents and lead to poor decisions being made (Dreyer and Oltedal, 2019; Endsley, 1995).

Out-of-the-loop performance issues and a lack of level 2 SA have been seen when high-level cognitive tasks are automated (Endsley and Kiris, 1995). These findings suggest that the higher-level understanding of the system state is compromised, affecting the operator's ability to diagnose faults and control the system (Endsley and Kiris, 1995). However, it has also been found that at higher levels of automation the operator's workload is reduced which can help them to maintain high SA (Endsley and Kaber, 1999). The relationship between the level of automation and SA has been found

to be highly context-dependent on the task and function that has been automated (Wickens, 2008). It will be important that the interfaces for RCCs are designed to support the operators in maintaining their SA, which will be challenging at higher levels of automation (Ahvenjärvi, 2016). There is also a need to find innovative ways of supporting operators getting back into the loop to take back control (Endsley and Kiris, 1995).

Mackinnon et al. (2015) investigated the concept of a Shore-side Control Centre (SCC) using participants with a maritime background. Participants were asked to carry out different MASS operation scenarios: navigation tasks, collision scenarios, engine component failures and precise manoeuvring (Mackinnon et al., 2015). There was high variability in participants' SA ratings depending on what role they had been assigned (Mackinnon et al., 2015). This suggests that there are a number of factors that prevent individuals from gaining appropriate levels of SA including command structure (Mackinnon et al., 2015). The findings suggested that participants lacked 'ship-sense' meaning they were unable to physically verify the data being presented (Mackinnon et al., 2015). This suggests that visual and/or auditory data may be necessary for a SCC to give operators the sense of being on board the vessel to increase their SA (Mackinnon et al., 2015). Similarly, Ahvenjärvi (2016) suggested that the provision of auditory feedback could help to maintain an operator's SA as they may be able to detect faults with critical equipment such as the rudders and main propellers.

SA is also important for collaboration in HMTs as it allows them to assess situations and make appropriate decisions in dynamic situations (Demir and McNeese, 2015; Millot and Pacaux-Lemoine, 2013). Although autonomous agents have different decision-making processes, it is still possible to develop communication protocols which can facilitate team SA being established (Schaefer et al., 2017). Team SA supports co-ordination of both the human and autonomous agents allowing them to carry out the overall team goal (Endsley, 1995; Schaefer et al., 2017). Without shared SA, incorrect assessments may be made by one member and potentially an incorrect decision being made (Schaefer et al., 2017). However, developing shared SA in HMTs may be difficult due to the lack of physical proximity between the agents in the system (Schaefer et al., 2017).

### **2.3.3 Design considerations for MASS and avenues for further research**

The seven themes identified from the literature were used to define design considerations for MASS (see Table 2.2), that could be used to help support operator decision-making within a MASS HMT. In addition, areas for further research into the HMT decision-making process and how operators in those HMTs can be best supported have also been suggested in Table 2.2.

Table 2.2 - Design considerations for MASS and avenues for further research identified in the review of the HMT decision-making literature.

Theme	Design considerations for MASS	Areas for further research
Decision Support Systems	<ul style="list-style-type: none"> <li>• Human-centred design approaches such as Cognitive Task Analysis and Hierarchical Task Analysis will be needed to ensure that MASS DSSs are designed effectively to support the operators in their tasks.</li> <li>• Consider how the design of MASS DSSs will affect operator’s workload when carrying out their tasks and where possible avoid high peaks in workload of operator’s carrying out supervisory tasks and trying to ensure that workload is kept at a constant level.</li> <li>• It will also be necessary to consider how the DSS can be designed to support communication and understanding between the MASS’ automated systems and the operator.</li> </ul>	<ul style="list-style-type: none"> <li>• Further investigation will be needed into how the design of DSS affect human performance metrics such as workload and SA at an RCC</li> <li>• Applying user-centred design approaches to the design of MASS DSSs.</li> </ul>
Trust	<ul style="list-style-type: none"> <li>• Consider how MASS operator training could be used to help MASS operators form accurate mental models, by giving operators experience working with the automated system and a better understanding of its capabilities, to promote appropriate levels of trust being formed.</li> <li>• Another consideration that will be important in the design of MASS systems is the level of transparency of the automated system, as it will affect the operator’s ability to understand the system’s processes and therefore their trust in the automated system.</li> <li>• The use of flexible approaches such as adaptive automation should be consider in the design of MASS systems where tasks are appropriate for human and machine control.</li> </ul>	<ul style="list-style-type: none"> <li>• Further investigation is needed into the appropriate level of transparency for the different automated systems used in MASS and how adaptive automation could be implemented to promote calibrated trust.</li> </ul>
Transparency	<ul style="list-style-type: none"> <li>• For the design of MASS systems, it will be important to consider the level of transparency of the automated systems so that operators have an appropriate amount information to allow them to make informed decisions. It has been suggested that system transparency can be improved by including information</li> </ul>	<ul style="list-style-type: none"> <li>• It will be necessary to further investigate what other types of information could be used to increase the transparency of the MASS system</li> </ul>

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	<p>such as communicating the system's goal, its plan of achieving that goal, its progress and the system's reasoning processes, these types of information should be considered when designing MASS systems.</p> <ul style="list-style-type: none"> <li>• Another consideration for the design of MASS systems will be how this information can be displayed and integrated within these displays for the operator, to increase task efficiency and promote appropriate reliance on the automated MASS systems.</li> </ul>	<p>without overloading the operation.</p>
Teams	<ul style="list-style-type: none"> <li>• For MASS it will be important that the operator role has been clearly defined and that they have an appropriate understanding of their role and the automated system's role in the overall goal of the system.</li> <li>• MASS systems designs will need to consider how communication and teamwork between the operator and automated system can be facilitated and ensure that the operator has the necessary task relevant information to allow them to make informed decisions.</li> <li>• When researching MASS HMTs, the level of fidelity should be considered carefully to increase the ecological validity of the findings.</li> </ul>	<ul style="list-style-type: none"> <li>• Further investigation will be needed into how different team structures and methods of communication will affect collaboration within the HMT for operating MASS specifically.</li> </ul>
Task/Role Allocation	<ul style="list-style-type: none"> <li>• The risks associated with the MASS system being designed should be considered to ensure that an appropriate level of automation is used for that system. If the operators are working with safety-critical systems, such as collision avoidance systems they still maintain an appropriate level of control and be involved in the decision-making process.</li> <li>• The tasks of the operator will also need to be considered in the design of MASS system as the operator's workload will be affected, adaptive automation could be used to reduce the operator's workload by creating flexibility with the MASS HMT.</li> <li>• The use of adaptive automation would need to take into account the type of task and be implemented in a way as not create a peak in workload as the operator hands over the task and takes back the task from the automated system.</li> </ul>	<ul style="list-style-type: none"> <li>• Future work could investigate how adaptive automation affects workload across a range of MASS operational scenarios, to explore how it could be implemented as not to create peaks in workload.</li> </ul>

<p>Accountability</p>	<ul style="list-style-type: none"> <li>• The level of control that the operator has within the system needs to be carefully considered depending on the risks associated with that system, to ensure that the operator maintains an appropriate level of control and is still involved in the HMT decision-making process.</li> </ul>	<ul style="list-style-type: none"> <li>• There is still a need to investigate accountability in HMTs further, as automated systems use higher levels of automation and there is less direct human involvement. However, it can be seen there is a need to look beyond the relationship between the MASS and operator when considering accountability and system-based approaches will be necessary to consider the wider influences such as the organisation's influence as well.</li> </ul>
<p>Situational Awareness</p>	<ul style="list-style-type: none"> <li>• Further investigation is required into what information will be needed for MASS operators to maintain their SA and how that information should be displayed to the operators.</li> <li>• Novel ways of supporting operator's SA will be required due to them no longer having the same environmental cues as they might do onboard so they may have a lack of 'ship sense' and they may become disengaged at higher levels of automation.</li> <li>• There is also a need to find innovative ways of supporting the MASS operator getting back into the loop and taking back control in the event of an emergency.</li> </ul>	<ul style="list-style-type: none"> <li>• Future work should investigate novel ways of supporting operator's SA particularly around how to display information that would have previously been a physical cue whilst onboard a ship.</li> <li>• There is also a need to find innovative ways of supporting the MASS operator getting back into the loop and taking back control in the event of an emergency.</li> </ul>

## **2.4 Application of the Decision-Making in Human-Machine Teaming Network Model to a UAV accident**

The use of the grounded theory to generate the themes from the literature on decision-making in HMTs is an exploratory approach. Thus, to provide an initial validation of the decision-making in HMTs model presented (Figure 2.2) it has been applied to a UAV case study. The use of case studies has been used in human factors research to show the validity of theoretical models developed from literature by applying them to real-world examples (Foster et al., 2019; Parnell et al., 2016; Plant and Stanton, 2012). The application of case studies has been used for adaptation in complex socio-technical systems (Foster et al., 2019), driver distraction (Parnell et al., 2016), decision-making in the cockpit (Plant and Stanton, 2012) and decision-making in tank commanders (Jenkins et al., 2010). A UAV case study has been selected to provide the initial validation for the network model because MASS operation shares similarities with UAV operation as both are operated from RCCs (see section 2.1.1 for a description of the similarities and differences in UAV and MASS operation).

### **2.4.1 Accident synopsis**

In the summer of 2018, the Watchkeeper 50 UAV crashed during part of a training exercise at West Wales Airport, see section 3.3.1 in Chapter 3 for further details of the accident including a timeline of events, location of personnel within the GCS and a summary diagram showing the UAV's path on the runaway. An accident investigation was performed and culminated in the publication of an accident report by the Defence Safety Authority (2019). In this case, the UAV failed to register ground contact when it touched down on the runway, so the UAV's system auto aborted the landing attempt and began to conduct a fly around to attempt another landing. However, the UAV deviated off the runway and onto the grass. The operator, seeing this deviation, then tried to manually abort the landing, but this was after the system's auto-abort had been engaged. The operator then decided to cut the engine, as they believed that the UAV had landed on the grass. However, the UAV had already risen to 40 ft in the attempt to land again, so when the UAV's engine was cut it began to glide and then crashed shortly afterwards.

Several contributory factors were identified by the Defence Safety Authority (2019). These are presented in Table 2.3 and show that multiple layers of the system were implicated in accident formation. For instance, it was found by the Defence Safety Authority that the action which caused the accident was pilot 1 cutting the UAV's engine (Defence Safety Authority, 2019). However, there were multiple pre-conditions such as the runway slope, crosswinds and the GCS crew losing SA. At

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the pre-condition layer, it was found that the causal factors were the GCS crew’s loss of SA and the deviation of the UAV onto the grass as these factors led to the decision to cut the UAV’s engine. Whereas factors such as the runway’s slope and the crosswinds contributed to the accident, as these affected the extent of the UAV’s deviation from the runway.

Table 2.3 - Summary of factors in the WK050 accident (Defence Safety Authority, 2019). Note: UAV (Uncrewed Aerial Vehicle), GSC (Ground Station Crew), CAME (Continuing Airworthiness Management Exposition), CAMO (Continuing Airworthiness Management Organisation).

Organisational Influences	Pre-conditions	Actions
Crew flying rates and currencies	The UAV deviating off the runway onto the grass	Pilot 1 pressing the UAV’s engine cut
Flight Reference Cards	Loss of SA by the GCS crew	Emergency Handling
Insufficient & Ineffective Simulators	Cross wind & Runway slope	
No air crew manual	Disengagement of the BETA loop & influence of Land Status Time Out	
Wind Component Table	GCS Manning	
Interactive Electronic Technical Publication		
No CAME/CAMO		

Casual Factors	Contributory Factors	Other Factors
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When analysing an accident involving a complex socio-technical system it is important to view the system as a whole to determine the root cause of an accident, rather than just focusing on the human operator of the system (Dekker, 2006). By viewing an accident in this way, it is possible to see the system errors which may occur at each level of the system and how they caused or contributed to the accident (Plant and Stanton, 2012; Woods, 2010). To view system error, it is important to look at each level involved in the lead up to an accident, which includes the organisational influences, and supervision if inadequate could lead to the accident. It also includes the pre-conditions which are factors that led to the unique situation occurring. By understanding the influence of these factors, the actions during the accident can then be put into context.

It can be seen in Table 2.3 that there were eight contributing factors and three other factors involved in the accident. Table 2.3 also shows how organisation influences and pre-conditions led to

the situation and the decision to cut the engine, which shows the importance of viewing the whole system. In this case, organisational influences such as the reference materials and training provided contributed to the accident. There were two Flight Reference Cards (FRCs) that were considered relevant and for both reference cards, the immediate action was engine cut. However, both cards lacked the requirement to check that the UAV was in free roll before taking this action. It was suggested that the FRCs were missing vital drills preceding the action to cut the engine, which may have avoided this accident. Another contributory factor identified was training simulators used as they lacked different failure and alert scenarios, which could have given the pilots experience in dealing with this abnormal scenario of no ground contact being registered and the deviation onto the grass. The role of each theme in decision-making in HMTs model developed previously will be shown using this case study to show its application. Figure 2.4 shows the results of the application of this case study to the interconnections between the themes within the decision-making in HMT model, showing the relevance of these interconnections in decision-making in HMTs.

### **2.4.2 Decision Support System**

In this case, the GCS crew had Air Vehicle Display Computers (AVDC) for each of the pilots and client displays showing the live video feed from the camera mounted at the back of the UAV, as shown in Figure 2.3. The camera on the UAV is designed for reconnaissance missions but is stowed away and turned round to face rearwards during the final stage of landing to protect it. The UAV's flight modes had been displayed throughout the incident on the AVDC, these modes were being monitored and read out by Pilot 1 during the landing sequence. Pilot 2 was monitoring the Warnings Cautions Advisories for the landing and the video feed from the camera now facing rearwards. After the UAV failed to register ground contact when it landed long of its touch down point, it auto aborted the landing attempt giving an auto-abort alert. The Automatic Take-Off and Landing System's (ATOLS) auto-abort caption on the AVDC was illuminated red. However, there was no audio alert associated with the caption and the caption had minimal visible indication on the AVDC display. Although, several other visual indications on the AVDC showed that the UAV was attempting to land again such as, flight mode, artificial horizon indicator, altitude readout and rate of climb value. However, in the high workload and stress environment, the illuminated auto-abort caption and other visual indicators on the AVDC were not spotted by the GCS crew.

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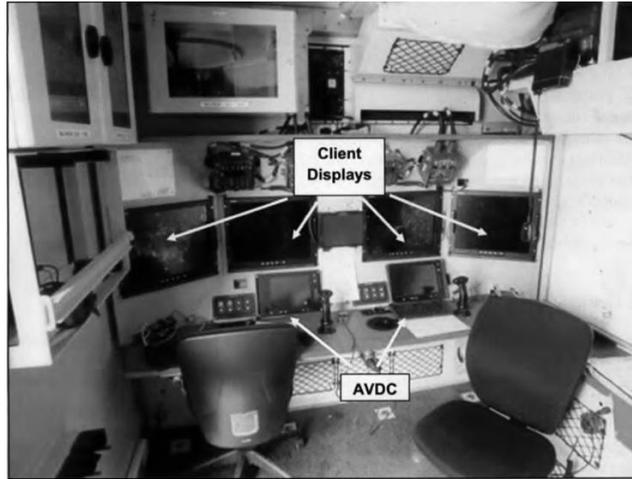


Figure 2.3 - Layout inside the Ground Control Station, the client displays which showed the video footage from the Watchkeeper and the Air Vehicle Display Computer (AVDC) used to operate the Watchkeeper.

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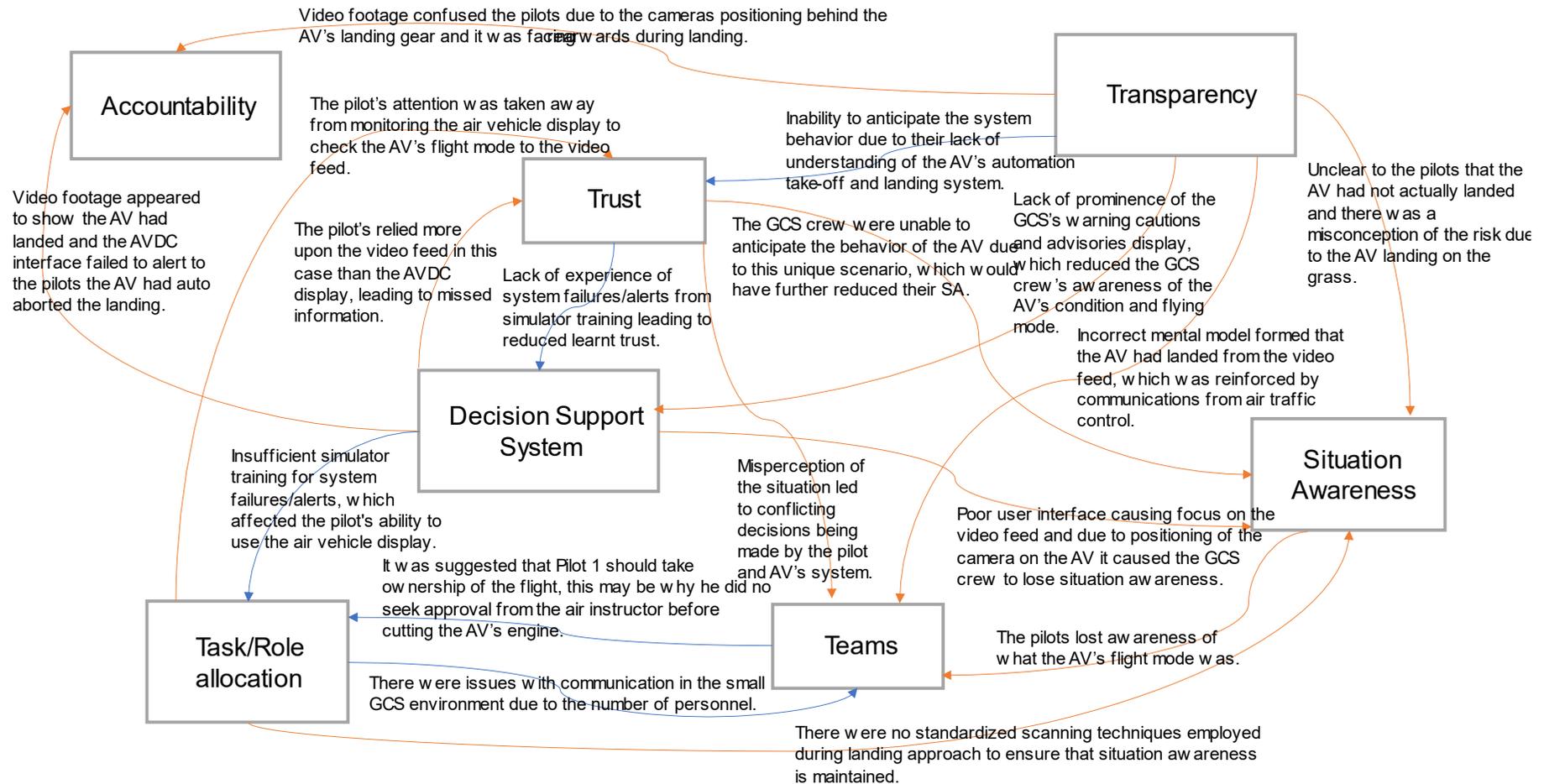


Figure 2.4 - The Decision-Making in HMT model showing the factors involved in the Watchkeeper accident and the interconnections between these factors for this case study. Note: Uncrewed Aerial Vehicle (UAV), Air Vehicle Display Computer (AVDC), Ground Control Station (GCS), Automatic Take Off and Landing System (ATOLS), Air Traffic Control (ATC) and Situation Awareness (SA). Colour code: orange connections relate to causal factors and the blue connections relate to contributory factors.

It has been demonstrated that poor interface design can lead to operators losing SA which then affects their ability to make decisions (Wahlström et al., 2015). In this case, the poor interface design of the AVDC meant that the pilots did not recognise the auto-abort alert, which would have informed them that the UAV was going to attempt another landing. It was suggested that warnings and cautions need to be made more prominent on the AVDC display, so pilots are less likely to miss the alerts in these high stress and workload situations. It was also suggested that the video feed was more compelling to the GCS crew than the AVDC display. Their attention was focused on the video feed, and it showed a full screen of grass making it look like the UAV had landed. Due to the positioning of the camera during landing (facing the rear of the UAV), even when the UAV began to climb into the air again it looked as though it was still close to the ground from the grass displayed on the feed. These factors meant that the GCS crew lost SA and incorrectly believed that they were dealing with a UAV which had landed but had deviated from the centreline and off the runway onto the grass. This led to pilot 1 deciding to cut the UAV's engine and the rest of the GCS crew who had also lost SA were unable to offer an alternative option.

### **2.4.3 Trust**

In this case, the GCS crew relied more upon the video feed suggesting that they may have had a greater level of trust in it than the AVDC display even though it gave information on the UAV's flight mode and its decision to auto-abort the landing. It has been found that communicating intent is a part of trust of forming trust, in this case, the communication between the pilot and the UAV system was ineffective. Although the AVDC display informed the pilot of the changing landing modes and the auto-abort, due to the poor user interface this was not an effective way to communicate this to the pilot. If the usability of the user interface of the AVDC display was improved, giving a better visual indication of the auto-abort or adding an audio alert it would allow the GCS crew to have greater levels of trust in it.

The insufficient simulator training in emergency handling scenarios would also have affected the GCS crew's learnt trust, which would have been lower due to their limited experience with these situations. This suggests that training with a DSS such as the AVDC display is an important factor in operators forming appropriate levels of trust. In this case, the GCS crew were unable to predict the behaviour of the UAV, due to the unique scenario that they had no prior experience. This inability to anticipate the system behaviour may have also been due to their lack of understanding of the UAV's ATOLS. This lack of understanding could potentially have reduced their level of trust in it also leading to reduced SA.

#### **2.4.4 Transparency**

The transparency of the system affected how the GCS crew dealt with the emergency, as they lacked knowledge of how the ATOLS worked. Specifically in this case, they lacked knowledge of the post ground contact sequence for the system, which may have affected their ability to diagnose the situation. An electronic document called the Interactive Electronic Technical Publication (IETP) is used to support the GCS crew, it contains technical, safety and maintenance about the Uncrewed Air System (UAS). However, the IETP was difficult to use, even an experienced instructor found it challenging to locate information within it on a specific part of the UAV's system. Although this was not a contributory factor in this accident, it affected the GCS crew's understanding of the UAV's systems and their ability to work with the UAV. However, it also highlighted the need for the GCS crew to have an overview of the systems without the in-depth technical information provided in the IETP, so they have a basic understanding of the UAV's functionality. If the GCS crew had more knowledge about the ATOLS and how it worked, they may have anticipated the auto-abort alert.

Therefore, it was suggested the GCS crews need a dedicated aircrew manual that would allow them to better deal with emergencies and enhance their understanding of the system. An aircrew manual would increase the transparency of the systems to the operators and allow them to make higher quality decisions, as they would have a greater understanding of the system. The video feed from the UAV also affected the transparency of the UAV to the crew. Due to its positioning behind the landing gear on the UAV the video appeared to show that the UAV had landed due to footage of the grass and that it was stationary. This incorrect mental model that the UAV had actually landed was also reinforced by the communications from air traffic control who transmitted the UAV had touched down and that it was right of the centreline.

#### **2.4.5 Teams**

In this case, the HMT was built up of five personnel in the GCS and the UAV. The five personnel were: the first pilot, the second pilot, the Aircrew Instructor (AI), the spare pilot and the Flight Execution Log Author (FELA). As the GCS is a small working environment and the pilots were only accustomed to being in the GCS with three people (the two pilots and their AI) having 5 personnel in the GCS made it feel cramped and increased the amount of chatter. It was suggested that the amount of talking increased the pilot's workload (Defence Safety Authority, 2019). For example, due to the small environment, the FELA had to obtain the information they required by asking the pilots as they could not see it on their screens. It was also found by the pilots that it was difficult to establish who was talking and whether they were giving an instruction or information, due to the audio quality on the headset and the number of people (Defence Safety Authority, 2019). At one point in the incident, after pilot 1 said abort and engine cut, the spare pilot said cut engine also. However, it was not clear

to the pilots whether it was the AI or spare pilot who said this as they were sitting behind them in the GCS (Defence Safety Authority, 2019).

It was also found that the situation encountered, the UAV departing from the runway onto the grass and an auto-abort alert with the video feed, could not be replicated in the simulator environment (Defence Safety Authority, 2019). It was suggested that more representative simulators were needed, that prepared pilots for a greater number of failures and alerts that they might experience operating the UAV (Defence Safety Authority, 2019). This would improve the GCS crew's ability to diagnose failures and gain experience using the appropriate emergency handling procedures.

### **2.4.6 Task/Role allocation**

In this case, one of the problems was the conflicting decisions made by pilot 1 and the UAV's ATOLS. The UAV's system had decided to attempt another landing as it had not registered ground contact. Whereas pilot one decided to cut the engine, as he believed that the UAV had landed on the grass and there were risks to life and equipment associated with the UAV deviating off the runway. It was also suggested in the briefing that pilot 1 should take ownership of the flight, this suggestion was made by the AI. This may have been why pilot 1 did not seek approval from the AI before he decided to cut the engine.

Emergency handling of this scenario was also found to be a contributory factor in the accident (Defence Safety Authority, 2019). There were no standardized scanning techniques employed during the landing approach to ensure that SA is maintained, which may have assisted the GCS crew in handling this emergency. The pilots' lack of simulator training for system failure or alerts would have affected their ability to know what actions may be suitable in that scenario and what cues they might look for. If they had experienced a situation where the UAV had deviated off the runway onto the grass and given an auto-abort alert in the simulator, they may have given more attention to monitoring the AVDC than the video feed. Therefore, they may have checked the flight mode on the AVDC to check that the UAV had landed before taking any emergency actions.

### **2.4.7 Accountability**

Table 2.3 shows the different factors involved in the accident, which shows the importance of viewing the whole system when looking at accountability, as there may be factors at different levels. In this case, many factors were outside of the GCS crew's control. For example, the crosswind may have contributed to the UAV leaving the runway and the slope of the runway would have exacerbated the effect of the crosswind on the UAV. The GCS crew's lack of knowledge of the UAV's ATOLS may have also contributed to them missing the auto-abort alert as they did not have an aircrew manual.

Although the cause of the accident in the accident report was said to be pilot 1 cutting the UAV's engine. It was found that there were wider system influences (Table 4) which caused the GCS crew to lose their SA, such as the poor interface of the AVDC which did not make the auto-abort alert clear to the pilots (Defence Safety Authority, 2019). The video feed from the UAV also contributed to the accident and affected the transparency of the situation, as it appeared that the UAV had landed from the video feed. As discussed previously if a human operator does not have full control over a system and lacks knowledge of how that system operates it raises the question of whether they are accountable for any incidents or accidents that occur (Simmler and Frischknecht, 2020; Taylor and De Leeuw, 2020). In this case, it was not clear to the pilots that the UAV had not sensed ground contact and that an auto-abort alert had occurred on the DSS (the AVDC). Therefore, the pilots were not aware that the UAV was going to conduct a go-around to attempt another landing, so there was no need to take emergency action to cut the engine.

### **2.4.8 Situation Awareness**

One of the causal factors in this accident was the loss of SA by the GCS crew, as they believed that the UAV had deviated from the runway and had landed on the grass. When the UAV had actually failed to detect ground contact and the system had auto aborted the landing attempt and was about to attempt another landing. This misdiagnosis of the situation led pilot 1 to decide to manually abort the landing attempt but this was four seconds after the auto-abort was engaged. Two seconds later, pilot 1 then decided to cut the UAV's engine causing it to crash. It was found that the poor user interface of the AVDC caused the pilot to lose their SA as there was no audio alert when the UAV went into a land status timeout (no ground contact established) and then to an auto-abort. The caption on the AVDC gave minimal visible indication to the pilots which allowed them to lose awareness of what flight mode the UAV was in which turned out to be crucial in this accident. Pilot 1 may have then realised that the UAV was making another landing attempt and other members of the GCS crew may have also realised this and may have been able to intervene.

In this case, the camera footage also affected their SA, it has been suggested that visual and auditory feedback may be useful in the operation of MASS to allow remote operators to maintain their SA (Mackinnon et al., 2015). However, this case shows that these feedbacks must be implemented carefully as they can potentially mislead operators if they are not combined appropriately with user interfaces. Although in this case, the camera's main function was not as a decision aid it was used by the pilots during the landing, other feedback channels may also need to be considered in certain scenarios and potentially turned off to avoid conflicting situations. It may be necessary to train operators when it is appropriate to use such features as support systems and when they should be ignored. The video feed was more compelling to the GCS crew when they were determining what had occurred than the AVDC display, which contained important information such as the flight mode.

In this case, it may have been more appropriate for the camera to have been switched off during landing to prevent it from causing any loss of SA.

## 2.5 Summary and Conclusions

The decision-making process in HMTs needs to be investigated further to explore how humans and autonomous systems can work cooperatively and effectively together. Many human factors challenges have been identified in the remote operation of MASS due to the nature of the human's role changing to a supervisory one. Monitoring will provide challenges as the effectiveness of the automation will depend on the human's reliance on it and the cognitive workload experienced by the human operators. There are also challenges in supporting communication and cooperation within a HMT.

A systematic review of the literature into HMT revealed seven themes: Decision Support Systems, trust, transparency, teams, task/role allocation, accountability and situational awareness. It will be important to consider how each of these themes influences decision-making within HMTs. Design considerations for MASS have been suggested from the review of the HMT literature. For MASS it will be necessary to consider how MASS DSSs can be designed to help operators maintain their SA and support communication and understanding within the HMT so that operators are able to make informed decisions. It has also been identified that trust will affect the operator's reliance on the automated system and there may be difficulties in the formation of trust for autonomous systems which hide their system processes from operators and the operators are no longer involved in the decision-making process. It was found that operators will need experience working with the automated system and an understanding of the system's capabilities. It will be important to consider how MASS operators are trained to give them a level of understanding and experience, to support appropriate levels of trust being formed. Another consideration for the design of MASS systems will be the level of system transparency used, to give the operators enough information to make informed decision and to help develop appropriate levels of trust, by giving the operators a greater awareness of the system's operation.

Another issue identified was how accountability will be determined as an autonomous system would be making decisions without the human's input, which may make it unclear where the human responsibilities lie. The MASS operator's roles and responsibilities will need to be clearly defined for that MASS and the levels of automation being used, so the operator understands their responsibilities within the HMT. It will also be necessary to consider the levels of automation that are used for the MASS systems depending on the levels of risks associated with the systems, to ensure that the operator is still involved in the decision-making process and could control the system in the event of a failure. An important design consideration for MASS will be how communication between

the operator and MASS system is established to give the operator an awareness of what their automated teammate is doing and to ensure they have the relevant information for their task. As the decision-making will be shared in the MASS HMT, it will be important to consider how to develop and support a shared mental model to allow for effective teamwork. Supporting the MASS operator's SA will be a key factor in their ability to make appropriate decisions, so what information is given to the operator and how it is displayed to them should be considered when designing MASS systems.

It has been shown that there are interconnections between some of these themes identified, which has been shown through the development of a Network Model for decision-making in HMT. A UAV case study was used to validate the Network Model because the operation of UAVs shares some similarities with operating MASS. The application of the UAV case study to the proposed Network Model for decision-making in HMT demonstrates its utility to capture the underlying considerations required in the future design and consideration of UAV usage and other uncrewed systems operating from RCCSs. The case study analysis showed how each of the themes in the model are applicable to highly automated UAVs and other highly automated uncrewed systems such as uncrewed MASS, which are also predominantly monitored by operators at RCCs. The decision-making in HMT model is intended to provide a basis for discussion and requires further refinement as research into this area progresses.

One limitation of this approach it does not consider the weightings of the interconnections between the themes found in the research; further research could investigate the different weightings of the interconnections identified. The decision-making factors in HMT model is intended to provide a basis for discussion and requires further refinement as research into this area progresses, as some interconnections between the themes may not yet have been researched and as research into this area progresses new themes may be developed. It will be necessary to further investigate decision-making in HMTs considering the limitations and problems introduced by automation and supervisory control and using the knowledge from the seven different HMT themes.

The following chapters of the thesis will use a mixed methods approach to investigate the seven decision-making factors identified in the decision-making factors in HMT model. The next chapter will investigate how decision-making is impaired and affected by operating uncrewed platforms from RCCs using the case study outlined in this chapter (section 2.4.1), to identify what lessons can be learnt for decision-making in HMTs.

# **Chapter 3 Maritime Autonomous Surface Ships: Can we learn from Uncrewed Aerial Vehicle accidents using the Perceptual Cycle Model?**

## **3.1 Introduction**

In the previous chapter, the decision-making factors in HMT model was developed from the themes in the literature and then a case study of an UAV was applied to the model to show the model's utility. The application of the use case showed how each of the seven factors: DSSs, trust, transparency, teams, task/role allocation, accountability and SA can affect decision-making in HMTs. The aim of this chapter is to investigate decision-making in uncrewed vehicle operation to understand the issues associated with their operation from RCCs. This will be achieved by using the same UAV case study from Chapter 2 to develop a Perceptual Cycle Model (PCM; Neisser, 1976) of the operator's decision-making process. This theoretical framework was chosen because it can be applied retrospectively, to understand why the operator made those decisions in terms of the wider system context, rather than focusing on the erroneous decision. It is important to consider why the decision made sense to the operator at the time they were made and what the underlying mechanism supporting their decision was. The analysis of the decision-making model developed will then be used to discuss potential design considerations for uncrewed systems such as MASS to better support the decision-making of the human operators. It will also be used to investigate what lessons may be learnt from operating UAVs from ground-based control centres and how the factors from the decision-making factors in HMT model can be supported. This user-centred approach has also been applied to investigate if there are additional interconnections within the decision-making factors in HMT model.

### **3.1.1 Error in uncrewed and automated operations**

It is envisaged that automated systems will be more reliable and can respond more quickly to situations than their human counterparts (Ahvenjärvi, 2016; Norris, 2018; Ramos et al., 2020). However, despite uncrewed systems having the potential to reduce error as the onboard human operator is removed, there is some concern that automation may create new avenues for error (e.g., Ahvenjärvi 2016; Burmeister, Bruhn, et al. 2014). This is because the role of the human operator is not entirely removed from the system, it is simply changed from an active operator to a supervisor of the system (Ahvenjärvi, 2016; Hoem, 2020). The errors that might be introduced may be new and potentially more complex, due to the complexity of the automated systems involved (Ahvenjärvi,

2016; Burmeister et al., 2014a; Hoem, 2020). This may have safety implications for MASS as it may then be harder for the human operator to diagnose and respond appropriately to a system failure or unexpected situation, so it may not be as simple as removing the human element from onboard to make systems safer (Sandhåland et al., 2015).

It will be necessary to consider the level of autonomy and level of automation of the MASS (see Chapter 1 for these definitions) when designing its systems, as it will affect the information required by human operators and what their responsibilities are (Man et al., 2018b). The level of control used is important as it describes the system's ability to operate without human input, showing that at higher levels of control or automation the operator may be less involved in the decision-making process as the systems are more highly automated (Scharre, 2015; Vagia et al., 2016). Whether the intention is for the MASS decision-making to have a high potential impact (e.g. collision avoidance navigation) or as an operator aid (e.g. proposing actions for a human operator to approve) it is critical to ensure that the information available to the operator is appropriate (Scharre, 2015). It has been found that automating decision-making functions can have a detrimental effect on a system performance (Parasuraman, 2000).

Another issue for decision-making could be less time for operators to make decisions at an RCC due to the potential delay in receiving information from the ship (Ramos et al., 2020). There may be a delay in the transmission of information from the ship because of the distance between the ship and the RCC and the time taken for the systems to process data transmitted from the onboard sensors (Wahlström et al., 2015). It has been suggested that the human-machine interface (HMI) will be critical for performance and safety, ensuring the operator maintains their SA and, in the loop, should they need to take over (Ahvenjärvi, 2016). There may be challenges in supporting the operator monitor the MASS' automated systems if they do not have an appropriate level of reliance on the automation (Parasuraman and Riley, 1997).

There are similarities in how MASS and UAV are operated as both platforms are operated from RCCs, but there are also some differences between the domains, for further details of these similarities and differences see section 2.1.1. These differences may limit the applicability of insights from UAV operations for MASS. Even though there are differences in operating MASS and UAVs from RCCs, the similarities in their operation mean that it is useful to consider the remote operating problems already experienced with UAVs and understand what lessons could be learnt for MASS.

It is expected that there will be multiple operator roles in the RCC, such as an operator monitoring the ship, an engineer and other team members, however, this would depend on the type of mission being carried out and the complexity of the MASS (Burmeister et al., 2014a; Mackinnon et al., 2015; Man et al., 2015; Saha, 2021). Multiple operator teams are also used in the operation of UAVs, such as multiple pilots, sensor/payload operators, an operation commander and other support personnel

depending on the type of missions and complexity of the systems in use (Armstrong et al., 2020; Giese et al., 2013; Gregorio et al., 2021; Man et al., 2015; Ruiz et al., 2015). For example, for the operation of surveillance UAVs teams of two are often used, a pilot and a video feed operator (Helton et al., 2015). It has also been suggested that there are three main roles in UAV operation, an operations director (for planning and coordination), a pilot and a mission specialist (in charge of operating the onboard sensors) (Peschel and Murphy, 2015). As technological capabilities advance, it is expected that single operators will be responsible for monitoring multiple uncrewed MASS (Andersson et al., 2021; Fan et al., 2020; Ramos et al., 2019). Similarly, the use of a single operator to control multiple UAVs is being investigated as the automated systems become more advanced leaving operators to supervise the UAVs (Jessee et al., 2017; Lim et al., 2021; Silva et al., 2017). Currently, the use of UAV swarms monitored by a single operator is being explored (Hocraffer and Nam, 2017).

In aviation, there have been numerous accidents involving UAVs (Giese et al., 2013). A study reviewed 68 US military UAV accidents between 2011 and 2014, it was found that 38% of the casual factors were categorised as unsafe acts and 53% of those unsafe acts were due to judgment and decision errors (Oncu and Yildiz, 2014). It is important to note that human error should not be used to explain the cause of an accident it should be the starting point for an investigation into why the error occurred (Dekker, 2006). Due to the similarities in the operation of both UAVs and MASS, similar decision errors could likely be seen in the operation of uncrewed MASS from RCC. It shows the importance of investigating the decision-making process in the operation of uncrewed systems, to understand why these decision errors were made and what can be done in terms of system design to better support operator decision-making. It has been highlighted that operators will still play an important part in the performance of the whole system, as they will be a backup if the automated systems fail and will need to be able to make appropriate decisions in potentially safety-critical situations (Kari and Steinert, 2021; Man et al., 2015).

### **3.2 The Perceptual Cycle Model**

The PCM is a model of information processing naturalistic decision-making model developed by Neisser (1976), which has been applied to naturalistic decision-making as the model links the decision-maker's thoughts with information available within the world (or environment), which goes on to influence their behaviour and actions. The concept of 'schema' is used to describe organized mental templates of a decision maker's thoughts or behaviours based on their past experience and world knowledge (Plant and Stanton, 2012). The PCM is a cyclical model (see Figure 3.1) in which world information that is available to the decision-maker modifies their perception of the environment and as a result may trigger their schema (Plant and Stanton, 2012). This then directs the

actions they take and then more information about the situation may be available to them as a result of their actions or due to the dynamic situation and the cycle begins again (Plant and Stanton, 2012). Their schema is activated by bottom-up processing as the decision-maker uses the world information to match their past experience, which then modifies their perception of the situation and leads them to potential actions they may take (top-down processing) (Banks et al., 2018a). One feature of naturalistic decision-making is that decisions are constantly being made due to the developing dynamic situation, the decision-maker will go round the PCM multiple times as the situation evolves. The decision-maker's schema may be adapted, or an alternative schema may be triggered. As the situation develops, the decision-maker's potential actions may also be altered (Revell et al., 2020).

The PCM will be used to explore decision-making in a UAV accident to investigate human-system relationships in the operation of uncrewed vehicles. To understand what can affect operators' decision-making processes when operating uncrewed vehicles from RCCs and gain insights into how MASS operators' decision-making could be supported. Even though at higher levels of automation the MASS operator's main responsibilities will be to monitor the ship's automated systems, their decision-making will still be important in the safe operation of MASS, as they will need to handle alerts given by the automated systems and intervene when the systems cannot handle a situation (Man et al., 2015). For example, the operator may need to be involved in navigation decisions due to the complexity of a situation or in the event of a component or system failure (Burmeister et al., 2014b; Liu et al., 2022a; Ramos et al., 2020). Therefore, it will be necessary to investigate how the decision-making process of MASS operators can be supported to promote the safe operation of MASS.

This decision-making model has been chosen as it has been previously used to investigate incidents involving human-machine interactions using case studies such as the Kegworth Plane crash (Plant and Stanton, 2012), the Kerang rail crash (Salmon et al., 2013) and the Ladbroke Grove rail crash (Stanton and Walker, 2011). Also, studies such as Banks et al. (2018) have used the PCM framework to investigate an accident involving another automated system, an automated vehicle accident. The accident which occurred on the 7<sup>th</sup> May 2016 involved a Tesla Model S which was being operated in Auto-pilot mode that crashed into a trailer that was crossing an intersection on a highway west of Williston, Florida (Banks et al., 2018a). In this case, the PCM framework was used to show how internally held schema can influence a decision-maker's actions and how potentially inappropriate schema of automated systems and their reliability can lead to fatal accidents (Banks et al., 2018a). This accident highlighted the issue of responsibility when humans use automated systems and how task allocation between the human and the system needs to be clear so humans are aware of their responsibility (Banks et al., 2018a). However, Banks et al., (2018) also demonstrated that vehicle manufacturers also have a degree of responsibility to support and facilitate the development

of appropriate schema, so that appropriate levels of trust are developed for the automated systems they design.

As shown by others (e.g., Plant and Stanton, 2012; Banks et al., 2018), the PCM framework can be used to explore system error in the human-system relationships, as it puts the human decision-makers thought process into the system context. The PCM framework shows how their decisions made sense at the time based on the information available and their interactions with the automated system (Plant and Stanton, 2012). Plant and Stanton (2014) established the validity and re-test reliability of the PCM by showing that it is valid for representing real-life data using the example of rotary wing pilots. By exploring system errors in this way, it can show what led the decision-makers to their decisions, to understand how their decision-making can be further supported in the context of the system they are operating. The application of a UAV case study to the PCM will be used to investigate the system errors that occurred in this case, to understand how similar issues might be prevented in the operation of MASS from RCCs and how MASS operator decision-making could be supported.

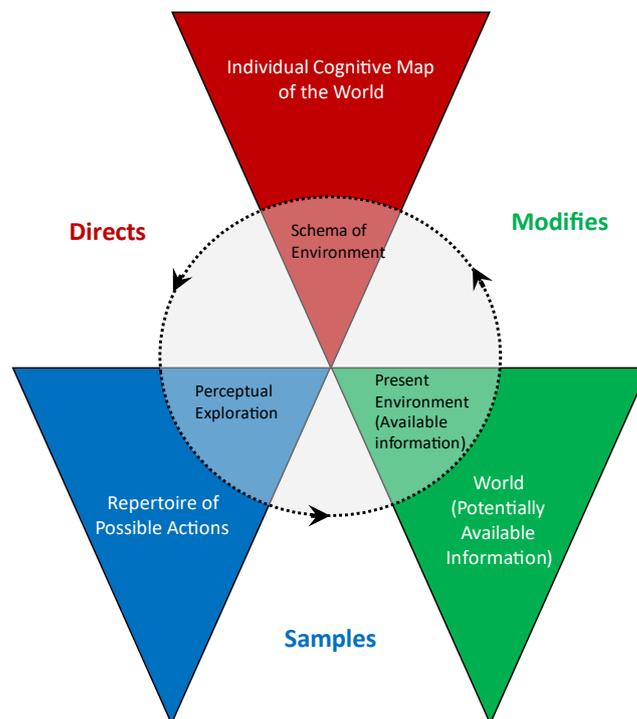


Figure 3.1 - The Perceptual cycle model (Neisser, 1976).

### 3.3 Case study of an Uncrewed Aerial Vehicle accident

#### 3.3.1 WK050 accident

The UAV (WK050) crashed during a captaincy training flight on the 13<sup>th</sup> of June 2018, for a summary of the accident and the contributory factors identified in the accident report see section 2.4.1 in

Chapter 2. Further details of the accident are provided to provide context for the subsequent analysis, including a timeline of events. The Watchkeeper is an intelligence, surveillance, and reconnaissance UAV and it has an automated system which controls take-off and landing and is monitored by the GCS personnel who can override the system if necessary. Each pilot was required to complete three flights in the first pilot role (pilot 1; who's in charge of monitoring the UAV's systems) and three in the second pilot role (pilot 2; who focuses on the reconnaissance mission). Six test flights were planned, however on the fourth flight, an accident occurred during the landing attempt. According to the accident report, the first pilot (pilot 1) had decided to land the UAV earlier than planned due to high crosswind gusts, as it was anticipated the high crosswinds may lead to several go-arounds before the UAV landed successfully. Whilst the training exercise took place there were five team members in the GCS, the two pilots, an aircrew instructor, a spare pilot and a flight execution log author, see Figure 3.2 for the control room layout and location of the personnel.

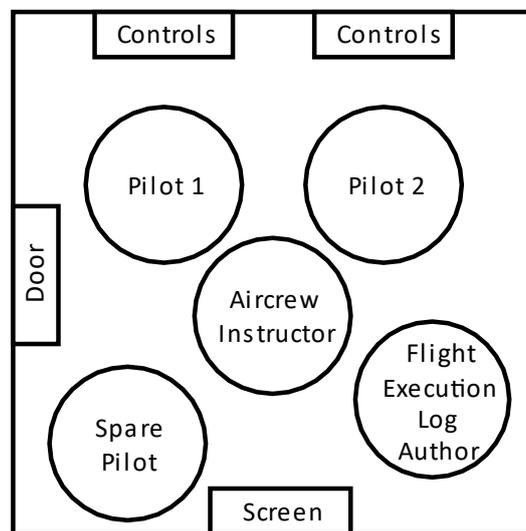


Figure 3.2 - Line drawing of the Ground Control Station setup.

Figure 3.3 shows a summary of the UAV accident showing the path of the UAV during the landing attempt, the landing stages and the points at which the system and manual commands were given. Figure 3.4 shows a summarised timeline of the events leading to the accident, which has been broken down into four phases: landing initiated, landing approach, ground touch window and emergency handling (Defence Safety Authority, 2019). It is important to understand the limited time sampling window the GCS crew had at each stage during the landing attempt. Figure 3.4 shows that pilot 1 decided to manually abort the landing four seconds after the ATOLS had already made the decision to abort the landing, then decided to cut the engine two seconds later. The decision to cut the engine had only been made nine seconds after the UAV had been seen deviating from the runway. The emergency handling stage was only six seconds long, showing the short time in which, the decision was made.

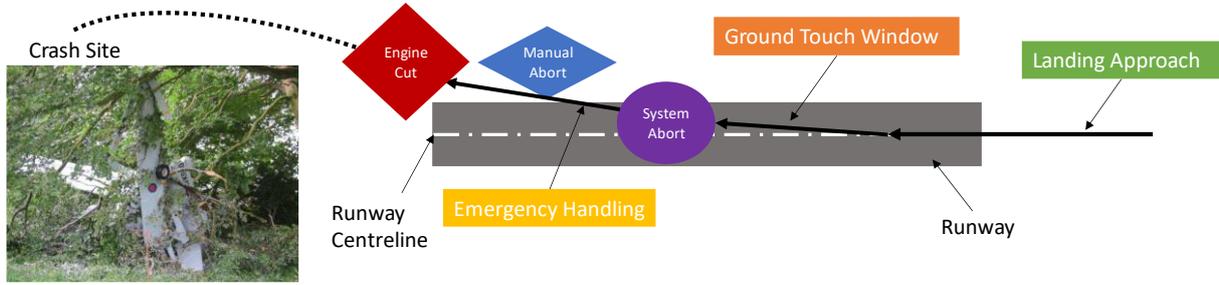


Figure 3.3 - UAV's path on the runway, the system alerts and manual commands given during the landing attempts. See Figure for the timeline of each of the landing stages.

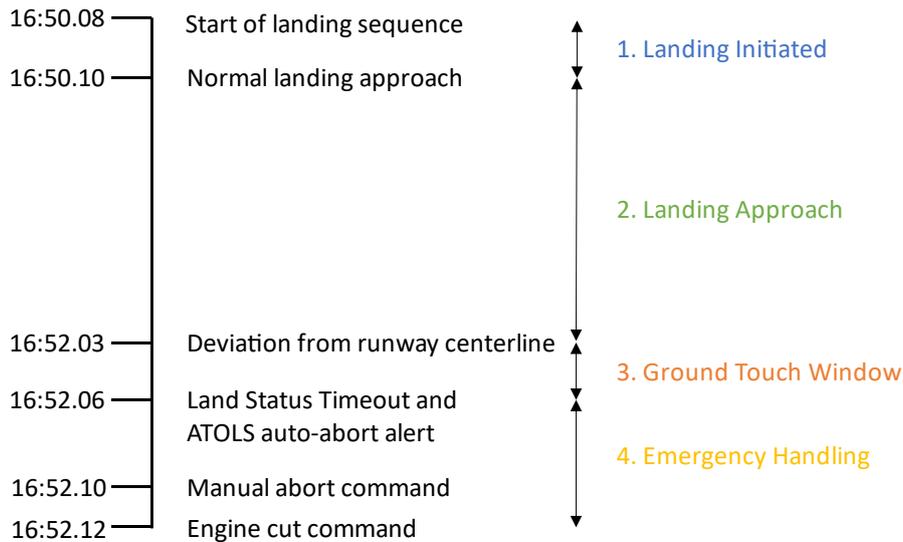


Figure 3.4 - Timeline of the WK050 accident (Defence Safety Authority, 2019). Note: Automatic Take-off and Landing System (ATOLS).

Often in the case of accidents like the WK050, the operators of these systems are found to be at fault and 'human error' is the cause of the accident (Dekker, 2001; Woods, 2010). However, it is important to consider the wider system context in these cases to understand why the accident occurred and why the operators made the decisions that they did, rather than just looking at the decisions they made (Dekker, 2001). In the maritime domain "human error" is often sighted as the cause of accidents but it is necessary to understand the root cause of why these errors were made (Chang et al., 2021; Kaptan et al., 2021; Luo and Shin, 2019). Although MASS are expected to remove some avenues of human error due to the change in the role of the human operator there is potential for new errors to emerge and it will be necessary to consider how higher levels of automation could affect the safety of operating MASS (Chang et al., 2021).

In the WK050 accident, it is necessary to investigate the thought processes of the pilots to understand why the decision was made to cut the engine. By analysing the accident from the point of view of the decision-makers it can show why these decisions made sense to the operators in that situation (Dekker, 2006; Plant and Stanton, 2012). The decisions made by the operator are

dependent on their understanding of the situation based on the information that was available to them at the time and their goals (Dekker, 2006; Dekker, 2011). Operators often experience competing goals in complex socio-technical systems, in which safety has to be weighed up against (Dekker, 2006). When investigating the cause of accidents it is necessary to consider organisational norms, operational pressure and regulations to understand the conflicting goals of the environment the operator is making decisions within (Dekker, 2006; Woods, 2010). By analysing decision-making in accidents and incidents using a systemic approach, different contributing factors at each level of the system can be shown (Woods, 2010). The risks identified using a systemic approach may then be used to investigate ways to mitigate these risks in the similar operation of future uncrewed MASS at RCCs.

### 3.3.2 Perceptual Cycle Model of the WK050 crash

#### 3.3.2.1 Model Development

The PCM was developed by a team of human factors practitioners and subject matter experts (SMEs) in an iterative cycle using the Defence Safety Authority (2019) accident report as a basis for discussion. SMEs were defined as members of the uncrewed system community with experience in UAV operations including academic and industrial stakeholders, for further details of the four SMEs' roles and their number of years of experience in the domain see Table 3.1. Information from the accident report was coded into one of three categories from the PCM framework: 'Schema' (based on their individual cognitive map of the world based on their experience); 'World' (the world information that was available to them) and; 'Action' (the actions they then took) and structured against the accident timeline, using the approach defined in Plant and Stanton (2013b). The data was then put into a model for analysis for uncrewed system operation recommendations.

Table 3.1 - Subject Matter Expert roles and number of years' experience in the domain.

<b>Industrial/Academic Role</b>	<b>Number of Years Domain Experience</b>
Technical Uncrewed Aerial Systems Director and Accountable Manager (Military Flying)	30
Visiting and Adjunct Professor	40
Project Design Authority for Uncrewed Aerial Systems/Remotely Piloted Aerial Systems	24
Head of Human Factors and User Experience	18

### 3.3.2.2 What happened during the landing attempt – “work-as-done”

Figure 3.5 shows the analysis of the accident using the PCM framework. The PCM developed (Figure 3.5) predominantly follows an iterative cycle from ‘World’ to ‘Schema’ to ‘Action’ and can be followed using the step numbering shown in the model. There was a pre-mission briefing for the GCS crew before the training exercise, typically this would include allocation of roles, local weather conditions and routes. As part of this briefing, it may have also been discussed that in other landing attempts at West Wales Airport there had been deviations from the runway centreline, so this may have become an expected behaviour for that particular runway in certain weather conditions.

The landing-initiated stage began when pilot 1 saw the crosswind gusts of up to 15 kts and made the decision to land the UAV. Pilot 1 then initiated the recovery and pre-landing checks, which included locating the manual abort button for landing. Pilot 1 also briefed pilot 2 for the landing, informing him that there would be no intentional manual aborts during the landing. At this stage, both pilots would have activated schema based on their past experiences of landing a UAV during crosswinds with no expected manual aborts. This experience may have been from previous flights or simulator training. During the landing approach, the UAV’s system reported the landing stages on the Air Vehicle Display Computer (AVDC) as expected. This was being monitored by pilot 1 who then read out each landing stage. Pilot 2 was monitoring the warning, cautions and advisories as requested by pilot 1 during the pre-landing brief. Pilot 2 was also monitoring the full motion video from the UAV to check the runway was clear. The landing progressed as normal, and it could be seen from the video feed that the UAV was visibly crabbing left but was still tracking the centreline. This led the pilots to believe that the landing was still progressing as would be expected for a UAV landing in crosswinds. Pilot 2 then stowed away the camera for landing, turning it to face rearwards. This is a standard procedure used to protect the camera from any insects or debris during landing. The UAV system continued to report the landing stages (‘semi-flare’ and ‘de-crab’), and these were read out by pilot 1. These were as the GCS crew expected for a crosswind UAV landing.

The ground touch window then began, with the video feed showing that the UAV had started to drift right off the centreline. This was recognised by pilot 2 but was incorrectly reported to other members of the GCS crew (i.e., pilot 2 called out that the UAV had drifted left of the centreline). This may have been a perceptual mistake as the camera was now facing rearwards. The deviation at this point was not unusual during landing at West Wales airport and may have become expected behaviour. Air Traffic Control (ATC) then reported that the AV had touched down, but it was long from the touch down point. This message may have activated the GCS crew’s ‘landed’ schema, as touch down normally meant that the UAV had landed. Pilot 2 then corrected his previous call of UAV left of the centreline to UAV right of the centreline, which was then confirmed in a call from ATC. At this point, the deviation of the UAV from the runway centreline was not unexpected as the UAV had

deviated in flights at that airport previously. This deviation may have supported the crew’s mental model of landing.

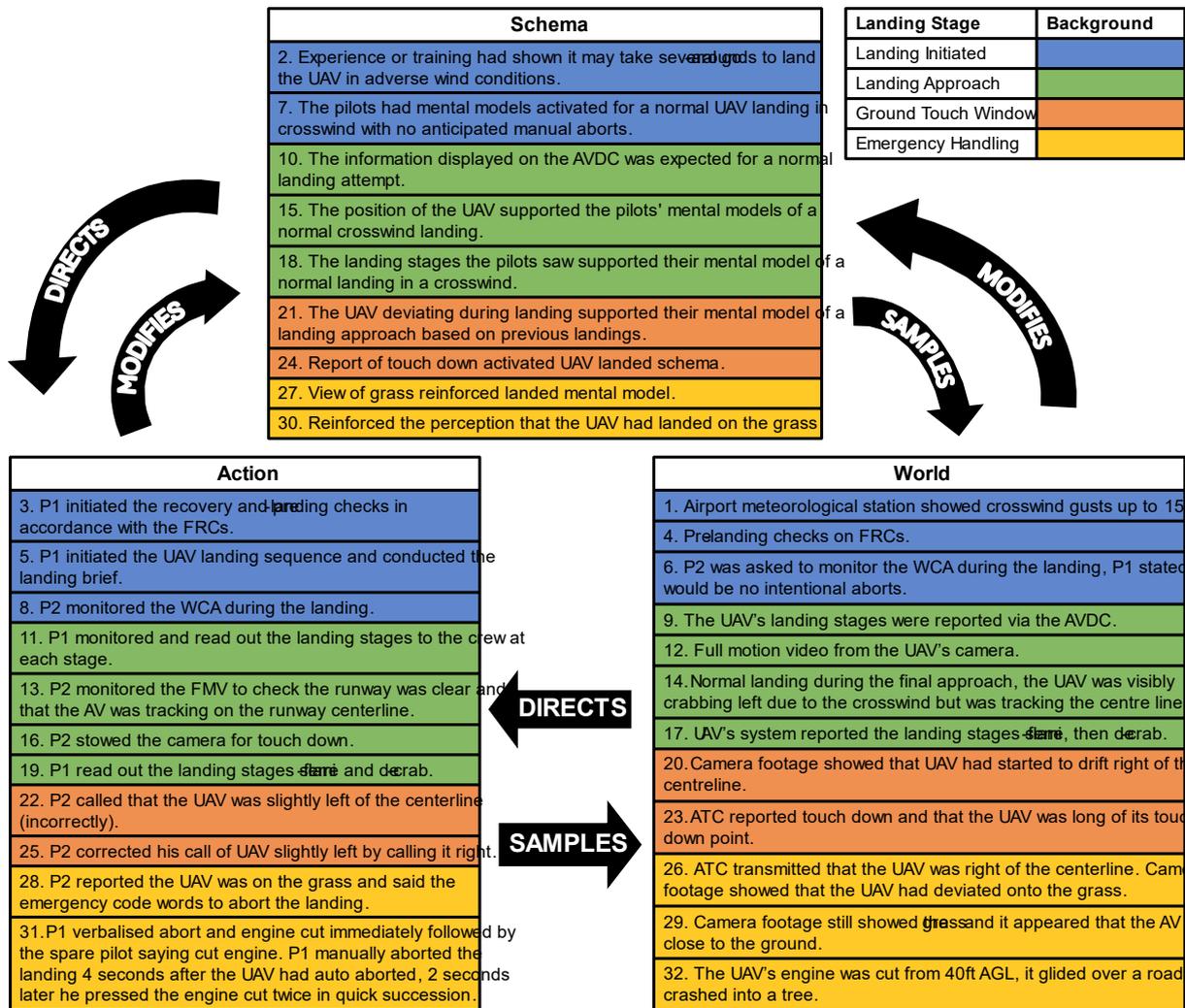


Figure 3.5 - Analysis of the Watchkeeper accident using the PCM framework (Neisser, 1976). Note: Pilot 1 (P1), Pilot 2 (P2), Uncrewed Air Vehicle (UAV), Full Motion Video (FMV), Flight Reference Cards (FRCs), Warnings Cautions Advisories (WCA), Air Vehicle Display Computer (AVDC), Air Traffic Control (ATC) and Above Ground Level (AGL).

However, the video feed then showed that the UAV had left the runway and had deviated onto the grass, which was reported by pilot 2. The GCS crew then believed that the UAV had landed on the grass. At this point the emergency handling stage began, the mental model that the UAV had actually landed could have further been reinforced by the message from ATC that the UAV was right of the centreline. As the GCS crew now perceived the situation as UAV had landed on the grass, pilot 2 said the emergency code words to abort the landing. The video feed showed the grass beneath the UAV which appeared to the GCS crew as stationary. The GCS crew had the existing knowledge from the WK’s landing trials that the UAV lost speed much faster than on the runway, so the engine cut needed to be activated quickly. Pilot 1 verbalised the intention to abort and engine cut, immediately followed by the spare pilot saying, “engine cut”. Pilot 1 then manually aborted the landing attempt

two seconds later than the UAV had auto aborted the landing. Pilot 1 pressed the engine cut button twice in quick succession. This then led to the UAV falling from 40 ft and gliding across a road into a tree. The GCS crew only had a six-second sampling window after ground contact had not been established and before the decision was made to cut the engine. This shows how compelling the video feed was to the GCS crew in deciding a course of action for their perceived situation.

### **3.3.2.3 What was supposed to happen during the landing attempt – “work-as-imagined”**

The WK has an Automatic Take-off and Landing System (ATOLS), which controls take-off and landing. ATOLS reports the stages in the landing cycle to the pilots through an Air Vehicle Display Computer (AVDC) so its progress can be monitored. One of the stages of the landing cycle is called ‘Ground Contact’ referred to as the ground contact window in Figure 3.3. If the ATOLS fails to detect ground contact during a specified window, it automatically aborts the landing attempt and begins to conduct a go-around so that another landing can be attempted. When the ATOLS decides to automatically abort the landing attempt, an auto-abort alert is shown to the pilots on the AVDC display. However, the system is designed so that the pilot can also step in and manually abort a landing attempt as a safety measure.

A PCM cycle has been developed to show what should have happened in this instance (see Figure 3.6). The ‘UAV had landed’ schema may have been activated by the message from ATC that the UAV had touched down (step 24 in Figure 3.6). This would have led to the expectation that the next landing mode shown on the AVDC would be ‘ground contact’ and then ‘free roll’. This would have meant that the UAV had established ground contact during the ground contact window, and it was now in free roll as would be expected during the landing phase. However, if the pilots had monitored the AVDC display they would have seen an auto-abort alert due to a land status time out and other indicators that the UAV was going around (e.g., the flight mode, climb rate, altitude, artificial horizon), rather than ‘ground contact’. This would have informed them that the UAV had not established ground contact and that the UAV was going to attempt another landing.

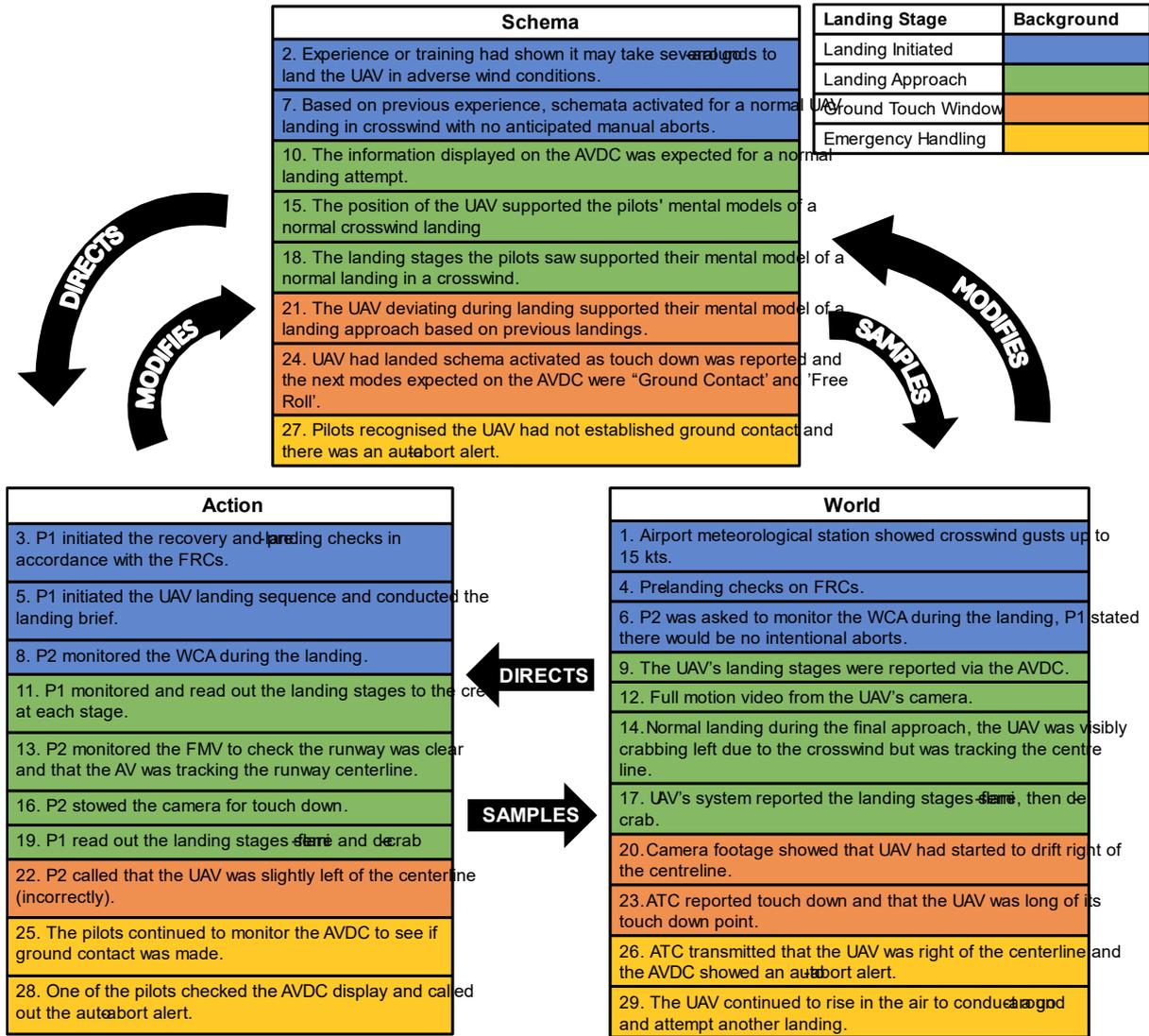


Figure 3.6 - Analysis of what could have happened in the Watchkeeper accident using the PCM framework (Neisser, 1976). Note: Pilot 1 (P1), Pilot 2 (P2), Uncrewed Air Vehicle (UAV), Flight Reference Cards (FRCs), Warnings Cautions Advisories (WCA), Air Vehicle Display Computer (AVDC), Full Motion Video (FMV) and Air Traffic Control (ATC).

### 3.3.2.4 Comparison of the “work-as-done” and “work-as-imagined” PCMs

The key difference between what actually happened in the WK050 accident (Figure 3.5) and what should have happened (Figure 3.6) is that the pilots’ attention was not on the AVDC and monitoring it for the expected landing stages ‘ground contact’ and ‘free roll’. The pilots were distracted by the video feed of the UAV on the grass. This distraction led to the misperception that the UAV had landed on the grass, if the pilots’ attention was on the AVDC the erroneous decision to cut the UAV’s engine may have been prevented. If the pilots had seen the auto-abort alert on the AVDC, it may have prevented pilot 1 from cutting the engine. However, the auto-abort alert on the AVDC display was not seen due to the distraction of the video feed and the minimal visible indication of the alert

(Defence Safety Authority, 2019). It was found that the AVDC interface was a contributing factor in the accident report (Defence Safety Authority, 2019).

The purpose of conducting a comparison between “work-as-imagined” versus “work-as-done” is that it enables us to highlight other potential weaknesses within the system. For instance, it may be that the auto-abort alert requires greater levels of saliency and pilots may need training on the use of the video feed in different scenarios. Also, pilots may need further training for unexpected situations to develop their emergency handling skills. It shows the importance of interface design in supporting pilots in maintaining their SA, including their awareness of an automated system’s mode. For MASS this suggests that the design of MASS HMIs and their associated alerts will be important in helping operators maintain their SA. It also suggests that the video feeds in RCCs should be considered carefully as their use could cause operator distraction in certain scenarios. Another issue highlighted was remote operator’s training for emergency scenarios to support their understanding and give them experience using the automated systems, to help them decide an appropriate course of action in the event of an alert or abnormal scenario.

### **3.4 Discussion**

Automation is often used as a tool to try and overcome errors from occurring however, it simply changes the type and nature of the errors that can occur as there is still a human monitoring the automated system (Dekker, 2006; Hoem, 2020). For uncrewed systems, it is still important to consider the human who will be monitoring the automated systems to ensure their safe operation (Woods, 2010). This is because whilst humans are no longer on board, they still play a key role in the safe operation of the system (Ahvenjärvi, 2016; Hoem, 2020). For instance, if there is a system failure or unexpected situation, operators at RCCs will have to decide a course of action and make appropriate decisions for the situation to mitigate any risks involved (Wahlström et al., 2015).

Typically, PCM models follow an iterative cycle from ‘World’ to ‘Schema’ to ‘Action’ and then back to ‘World’ and so on. However, Revell et al., 2020 recognised that it is possible decision-making can be bi-directional between model components (e.g., World-Action relationships). The analysis of the WK050 suggests such interactions were also present. World-Action relationships can be seen in step four to five and step twelve to thirteen in Figure 3.5, where the world information directed the pilots’ behaviour. For example, pilot 1 initiated the pre-landing checks in accordance with the flight reference cards and pilot 2 monitored both the video feed to check the runway was clear and checked to see whether the UAV was following the centreline of the runway. These World-Action examples show skill-based behaviour whereby the decision maker recognises and understands information available within the world. This would immediately trigger a response by the decision maker (Plant and Stanton, 2015; Revell et al., 2020). In the case of UAV flight, pilots follow set

landing procedures, perform landing checks and monitor the video feed enabling the schema node to be skipped as pilots are already aware of the action, they need to take (Plant and Stanton, 2015; Revell et al., 2020).

#### **3.4.1 Recommendation 1: identifying key information requirements for MASS systems**

To support operators at the RCC it will therefore be important that human operators have the necessary information to maintain their SA to make informed decisions to ensure system safety UCD approaches should be used during the system's design to capture these information requirements for different operational scenarios (Endsley and Kiris, 1995; Harris, 2007; Onnasch et al., 2014; Porathe et al., 2014). If the operator does not have adequate SA it can lead to erroneous decisions being made and potentially lead to incidents and accidents (Endsley, 1995).

In the WK050 case, it was a loss of SA of pilot 1 and the rest of the GCS crew, which was identified as a causal factor in the accident report (Defence Safety Authority, 2019). This led to the formation of a mode error (Norman, 1983; Sarter and Woods, 1995), which can occur when an operator loses awareness of the system's mode, leading them to make potentially inappropriate decisions as they may believe the system to be in a different mode than it is. In this case, the pilots were no longer aware of what mode the UAV was in and had believed it had landed. Figure 3.5 shows how the pilot's mental models affected their view of the situation leading to their belief that the UAV had landed. It also shows how the world information, the video feed and the messages from ATC confirmed their belief that the UAV had landed on the grass. The pilots may have been distracted by the UAV's video feed during the landing. However, the camera was not designed to be used as a decision support system. Instead, it was intended to be used for intelligence, surveillance, and reconnaissance only. It may be that the video feed needs to be switched off during landing or pilots may need to be trained when it is appropriate to use the video feed, as it may not always be clear what is actually happening. For instance, the camera is turned to face rearwards during landing to protect the lens, so pilots would only have a partial view of the situation. This finding shows the importance of supporting operators through system design to ensure that they can maintain their SA when operating highly automated systems (Endsley and Kiris, 1995; Onnasch et al., 2014; Porathe et al., 2014).

#### **3.4.2 Recommendation 2: exploration of alternative feedback mechanisms**

There is also a need to consider the types of feedback systems that can be implemented to alert operators as vigilance may become an issue when working with highly automated systems, both visual and auditory feedback has been suggested for RCCs but the different modes of feedback may distract operators from other important information in high workload and high-stress situations (Ahvenjärvi, 2016; Mackinnon et al., 2015). The use of video feeds will also be relevant for MASS as

their systems and systems designs include the use of onboard cameras providing feedback to operators at RCCs, which suggests that the video feed from the MASS could distract operators in high-stress and workload situations (Balbuena et al., 2017; Dobref et al., 2018; Giordano et al., 2016; Stateczny and Burdziakowski, 2019; Wang et al., 2016; Wu et al., 2022). Osga and Williams (2015) found that the addition of visual and audio feedback in the design of a MASS HMI improved task performance in a range of different tasks, such as collision avoidance, alarm response, system controls and waypoint reports tasks. Although initial investigations into the design of the MASS HMI highlighted the high risk of mode errors occurring due to the operators becoming distracted, suggesting a similar situation to this case study could occur in the operation of MASS (Osga and McWilliams, 2015). It was also found that in the design of the MASS HMI that the rear camera view from the MASS could be distracting to operators whilst carrying out visual tasks (Osga and McWilliams, 2015). This further suggests that the use of visual feedback will be an important factor in helping MASS operators maintain their SA, however, there is a need to consider how this visual feedback is implemented to not cause distraction and it has also been suggested that as MASS will be operated at slower speeds than UAVs the video may not always be necessary (Wahlström et al., 2015).

The pilots missed the auto-abort given by the UAV's ATOLS on the AVDC, this highlights the need to consider how interfaces and alert systems are designed for operation from an RCC. It has been found that deficiencies in the design of UAV HMIs have contributed to many UAV accidents (Friedrich and Lieb, 2019; Hobbs and Lyall, 2016; Wild et al., 2017). It may have been that the alert needs to be larger or its position on the interface needs to be more prominent (Phansalkar et al., 2010). An audio alert could also be added to the auto-abort alert to get the pilots' attention, as their workload may be high during landing, and they could be distracted by the video feed and not looking directly at the AVDC (Morris and Montano, 1996; Nakashima and Crébolder, 2010; Olmos et al., 2000).

Due to the similarities in their operation, the HMI will also be an important factor in the operation of MASS as it connects the human operator to the uncrewed vehicle (Hobbs and Lyall, 2016; Liu et al., 2022b; Terwilliger et al., 2014). The design of interfaces at RCCs will affect the operator's ability to maintain their SA and therefore their ability to make appropriate decisions, for MASS novel ways of supporting the operator to maintain their SA will be required (Chen et al., 2007; Endsley, 1995; Endsley, 2003; Miller and Parasuraman, 2007). It has been shown that for MASS collision avoidance the HMI will need to be designed appropriately to allow operators to interpret the information correctly, alert them to possible collisions and allow them to take the necessary actions (Ramos et al., 2019). The design of these alert systems for MASS will need to be carefully considered to ensure they are effective in gaining the operator's attention and then that the HMI supports them to take the action to avoid collisions, as this case has shown it may be necessary to have audio alerts associated with visual alerts and ensure that any visual alerts are prominent on the HMI. Virtual

Reality (VR) and 3D HMIs have also been suggested to improve an operator's SA at RCCs (Andersson et al., 2021; Karvonen and Martio, 2019; Lager et al., 2019). It has been found that VR and 3D human-machine interfaces improved participants' SA and improved their ability to detect collisions (Lager et al., 2019). Also, the use of a virtual environment simulating the audio from an engine room has been suggested to allow engineers at RCCs to better diagnose engine failures (Michailidis et al., 2020).

### **3.4.3 Recommendation 3: training and command structures for MASS**

The findings have shown that training and experience with automated systems can have an impact on their safe operation, highlighting the need to consider how automation training can be implemented within existing maritime frameworks (Deling et al., 2020). Pilot training and experience was highlighted as contributory factors to the WK050 incident (Defence Safety Authority, 2019). Training has also been found to be a factor in many maritime accidents as well (Chauvin et al., 2013) and it has been highlighted as an important factor in the safe operation of MASS (Jo et al., 2020b; Sharma and Kim, 2021; Yoshida et al., 2020). In the case of WK050, the pilots had not experienced a UAV deviating off the runway and the flight simulator was not capable of generating a scenario depicting a land status time out combined with a UAV departing from the runway and a video feed (Defence Safety Authority, 2019). This meant that the GCS crew faced a unique situation in which they were not equipped with the knowledge of the correct emergency procedure to follow or an accurate mental model of the situation. This suggests that training simulators need to be more representative of a larger number of emergency/system failure scenarios, to support pilots in developing accurate mental models. There are approximately 71 simulated emergencies on the WK simulators for the emergency procedure training (Defence Safety Authority, 2019). However, there are 760 failures and alerts on the WK system (Defence Safety Authority, 2019). Although it would not be feasible to expect all these scenarios to be covered, it might suggest that the pilots require more training scenarios to reduce the likelihood of another unique situation occurring.

This also has potential implications for MASS operators as they are expected to act as a backup to the automation and it has been suggested that simulator training may be used, so it will be necessary to consider the fidelity of those simulators and the range of scenarios that can be simulated (Hwang and Youn, 2022; Yoshida et al., 2020). It was also found that in the WK050 accident, the GCS crew lacked knowledge about the ATOLS which would be an important part of the GCS crew's expectations relating to each stage of the landing and the system's auto-abort (Defence Safety Authority, 2019). Simulator training has been found to give users a greater awareness of how a system works and could give remote operators greater experience working with the MASS' automated systems (Koustanai et al., 2012). Simulator training for abnormal situations has also been highlighted as a way to mitigate risks and allow operators to develop appropriate mental models in other domains such as

rail (Tichon, 2007), medicine (Baker et al., 2006), manual road vehicles (Roemaker et al., 2003) and automated road vehicles (Ebnali et al., 2019; Krampell et al., 2020). For MASS it will be necessary that operators have the required knowledge of the ship's automated system to allow them to make appropriate decisions, suggesting that appropriate simulator training may be a way to achieve this (Jo et al., 2020b; Sharma and Kim, 2021).

There were other factors involved in the accident, for example, the GCS was manned by five personnel in this case because it was part of a training exercise. However, the pilots were only used to three personnel (the two pilots and an aircrew instructor) being present in the small GCS unit. This caused communication confusion inside the GCS. At one point the spare pilot had said engine cut but the pilots were unable to distinguish who had said this, as the other three personnel were behind them in the GCS (Defence Safety Authority, 2019). As the flight was part of captaincy training there was not a clear command structure, as the aircrew instructor had said pilot 1 should take ownership and lead the flight, but it may have been that pilot 1 should have checked for agreement with the aircrew instructor before cutting the UAV's engine (Defence Safety Authority, 2019). This highlights the need for clear command structures in the operation of uncrewed systems, so the role and responsibilities of each team member are clear (Voshell et al., 2016). There were also environmental factors, strong crosswinds and the slope of the runway at West Wales Airport which also contributed to the accident (Defence Safety Authority, 2019).

For the operation of MASS, this accident highlights the need to carefully consider the training requirements for operators and ensure that operators are trained for abnormal scenarios as well as normal operations. The accident showed the importance of the RCC HMI requirements and a need to consider how warning systems are designed to inform operators. It also showed the need to consider how individual subsystem components may be used in MASS operation and to use human factors methods early in their design lifecycle to identify potential errors early on, so the risk of these errors can be mitigated. This example has shown the need for clearly defined roles of the operators working in an RCC, such as a shore-side control centre or host-ship for MASS operation and how the individual roles relate to the rest of the HMT. It will be necessary that MASS operators have appropriate pre-mission briefs so that operators are aware of any relevant information related to previous missions, such as the ship's behaviour at a specific location or environmental conditions.

The analysis of the accident using the PCM showed how decision errors can occur due to the difficulties in operators maintaining their SA when operating uncrewed vehicles from RCCs. Further, it demonstrates the potential for technology to be used in unanticipated ways that may go on to affect how decisions are made, showing that human factors methods need to be applied early in a system's design lifecycle. In this case, the video feed appears to have had a distracting effect leading to the pilots losing SA, which also could happen when operating MASS as operators will also have

video feeds at RCCs and could potentially have a restricted view of the situation. It showed how learnt behaviours can influence expectations of uncrewed system operation, such as the pilots becoming used to the deviation during landing at an airport. This accident highlighted the importance of the operator's mental models, it has been suggested that simulator training of different MASS system failures could be used to support operators in developing appropriate mental models, by giving them a greater awareness of what to expect in these situations. The accident also showed that the HMI is an important system component as it supports the operator in maintaining their SA and making appropriate decisions. It will be necessary to consider each of these factors could influence the operation of MASS from RCCs, as similar difficulties in decision-making may be encountered due to the similarity's operations between MASS and UAVs. Further work is needed to investigate decision-making specifically for MASS operation, to understand how it may be supported, what potential errors may occur and how these can be mitigated. Further work is also required to understand how MASS HMIs can be designed to support operator decision-making and to develop novel ways of supporting operators in maintaining their SA at RCC. The use of simulator training for MASS operators should also be investigated further to understand how appropriate mental model development can be supported.

### **3.4.4 Evaluation**

A limitation of using this approach is that it relied on the completeness and methods used in generating the Defence Safety Authority's accident report, but this was also supplemented with the discussions with SMEs. There are also the effects of hindsight bias to consider when analysing accidents after they have occurred and the subjectivity of developing the decision-making models from the reports. However, the PCM has been used previously to investigate single case study accidents, such as an automated vehicle accident (Banks et al., 2018a) and an aviation accident (Plant and Stanton, 2012), to understand why errors occurred in highly complex socio-technical systems and gain insights into what can be learnt from these accidents. Another limitation is the differences in the operation of UAVs and MASS from RCCs as MASS are operated at slower speeds and only navigate in two dimensions, which may limit the ability to generalise the findings to MASS (Praetorius et al., 2012). However, both uncrewed vehicles are operated from RCCs, so operators experience the same lack of proximity to the vehicles and difficulties in maintaining their SA and both are safety-critical domains (Ahvenjärvi, 2016; Gregorio et al., 2021; Kari and Steinert, 2021; Man et al., 2018a; Man et al., 2015; Skjervold, 2018).

### 3.5 Conclusions

As automation technology is becoming more intelligent, uncrewed systems are now being used more widely such as MASS in the maritime domain (Ahvenjärvi, 2016; Norris, 2018; Porathe et al., 2014). The introduction of these uncrewed systems is changing the role of the human operator to supervisors (Mallam et al., 2020; Nahavandi, 2017), which has the potential to introduce new avenues of failure in the system (Ahvenjärvi, 2016). This change brings certain challenges for decision-making as operators are now working with highly automated systems, which are also making decisions of their own, coupled with a reduction in SA from working beyond their line of sight (Mackinnon et al., 2015; Man et al., 2018b; Porathe et al., 2014).

The PCM has been used to investigate the decision-making process of pilots operating a UAV from a ground RCC, to understand how decision failures can occur during uncrewed vehicle operations at RCCs. Using the PCM in this way is beneficial as it shows the operator's decision-making process in the context of the system they are working with so that the breakdown in the human-machine relationship can be seen (Banks et al., 2018a; Plant and Stanton, 2012). The PCM highlights how the schemata of the decision-makers (the pilots) and the environmental information they had from the world led to the decision to cut the engine (Plant and Stanton, 2012). It is necessary to use such an approach to explore system failures in order to provide a causal explanation of why decisions were made, rather than just what decisions were made, to then be able to understand how accidents might be predicted or prevented in future (Banks et al., 2018a; Plant and Stanton, 2012). By understanding why a decision was made, possible mitigation strategies can be suggested, to better support operators' decision-making processes when operating uncrewed vehicles such as MASS.

This chapter has shown how the PCM can be used retrospectively to understand an RCC operator's decision-making to identify lessons that can be learnt for the factors that impact decision-making in HMT from RCCs. The next chapter will explore how the PCM can be used prospectively to generate insights into MASS operator decision-making and investigate the decision-making factors from the model, to generate user-centred design and training principles for future MASS systems. It will show how the PCM can be used prospectively in the early design stages to generate principles before the system or end users exist and identify further interconnections between the decision-making factors.



# **Chapter 4      Generating design and training principles for supporting decision-making in the operation of uncrewed Maritime Autonomous Surface Ships using the Schema Action World Research Method**

## **4.1      Introduction**

The previous chapter explored decision-making in RCCs in a similar domain using the PCM to investigate further the decision-making factors identified in Chapter 2. It demonstrated the challenges of operating uncrewed vehicles beyond line of sight and showed the potential for technology to be used differently from the expected way they were designed. This chapter builds on this analysis by investigating the decision-making of uncrewed MASS operators. This chapter aims to explore MASS operators' decision-making at RCCs using a user-centred approach to understand how their decision-making processes can be supported to help operators overcome the challenges of operating highly automated systems remotely. This will be achieved by developing design and training principles to support the future development of MASS. The design principles and findings from this chapter and the following chapters will be used to extend and refine the decision-making factors in HMT model developed initially in Chapter 2.

### **4.1.1      Decision-making in MASS operations**

MASS operators will have challenges in making decisions when operating uncrewed MASS from RCCs (degree three) due to their lack of proximity and working with highly automated systems, as detailed further in Chapter 2, section 2.1.2 (Han et al., 2022; International Maritime Organisation, 2023; Man et al., 2018b). At the RCCs, operators will be predominantly 'on the loop', where their main actions will be supervising the automated systems and taking back control if the system has an issue or cannot handle a situation (Madsen and Kim, 2024). It has been discussed that the majority of tasks associated with low stress will be automated in future MASS systems (Tam et al., 2021). However, operators will be responsible for taking back control in potentially high-stress situations and, therefore, need appropriate training to practice handovers (Tam et al., 2021). Automation acceptance can also be an issue for higher levels of automation, particularly when it affects the operator's involvement in the decision-making process, and their prior exposure to the automation can influence their acceptance (Bekier and Molesworth, 2017).

A challenge will be operators remaining vigilant to changes whilst monitoring the highly automated systems due to the issues associated with operators continuously monitoring automated systems for long periods (Endsley and Kiris, 1995; Parasuraman and Riley, 1997; Warm et al., 2008). Cognitive underload has already been seen in the operation of conventional vessels and could be exacerbated by the use of higher levels of automation (Cham et al., 2021). The concern with cognitive underload is that it can reduce performance when the workload transitions from low to high levels when an operator needs to intervene in a task (Young, 2021; Young et al., 2015).

This automation effect has been seen in other domains, such as automated driving and engaging operators with secondary tasks and using adaptive automation has been shown to reduce these effects in automated driving (Byrne and Parasuraman, 1996; Cheng et al., 2024b; DeGuzman et al., 2022; Gold et al., 2018; Mishler and Chen, 2024). Passive monitoring behaviour could cause a decision latency as operators will need time to get back into the loop to make an informed decision (Mackinnon et al., 2015; Man et al., 2018b). Delays caused by communications links could cause latency in the information being received from the MASS, which would affect the operator's decision-making time (Rødseth et al., 2013; Veitch et al., 2024). These information delays could become particularly important when responding to takeover requests or unanticipated situations (Rødseth et al., 2013; Veitch et al., 2024).

Another challenge for operators' decision-making will be maintaining their SA as they will lack the physical cues they would have when operating onboard a conventional vessel (Man et al., 2018b; Porathe et al., 2014; Ramos et al., 2019). A complication for uncrewed MASS is that operators will rely on the information provided by their technological systems to inform their SA (Han et al., 2022). MASS operators will utilise information from similar systems as a conventional vessel to navigate, such as an Electronic Chart Display Information System (ECDIS) and radar; the difficulty will be they will not have the physical cues to verify the digital information being presented to them (Man et al., 2018b). As operators will be using solely digital information, it will be important that they are provided with the necessary levels of information to inform their decisions without causing cognitive overload (van de Merwe et al., 2024). Kristoffersen (2020) developed five guidelines for supporting an operator's SA at a shore RCC by conducting a literature review. These guidelines were to ensure that RCCs are designed to keep operators in the loop, replace the operators' sensory cues, give operators an appropriate amount of information, provide automation transparency, and an indication of the automation level (Kristoffersen, 2020). Features such as path planning that show a planned route for collision avoidance have been suggested to increase the explainability of the automation (Veitch and Alsos, 2021). However, the level of displayed information on the automated system's working should be carefully considered so as not to overload the operator (Veitch and Alsos, 2021). The use of trial collision avoidance functions that show the predicted outcome and

information on which rule is being followed and what the system has used to make its decision (Madsen et al., 2023).

### 4.1.2 Schema World Action Research Method

The Schema World Action Research Method (SWARM) developed by Plant and Stanton (2016) is an interview schedule that is theoretically underpinned by the PCM framework (see section 3.2 in Chapter 3 for a description of the PCM). SWARM will be used to understand what information and experiences MASS operators will utilise when making decisions. SWARM was developed to capture how pilots make critical decisions and gain insights into their decision-making processes by applying the PCM framework (Plant and Stanton, 2016a). SWARM is an interview method that uses sets of cognitive prompts for the three PCM components (Schema, Action and World) to investigate how decisions are made. SWARM captures insights into what information the decision-maker uses in their environment to shape their understanding of a situation. It also shows how they use their experiences and knowledge to act and make decisions.

SWARM has been selected to investigate MASS operator decision-making as previous applications have shown how SWARM can be used to generate user-centred design and training recommendations to support the interactions within an HMT (Banks et al., 2021; Parnell et al., 2021a; Sturgess et al., 2024). For example, it was suggested that to aid pilots in identifying an engine oil leak, a graphical representation of the oil trend over time could be displayed and automatically present the relevant checklist for the action selected (Banks et al., 2021). To aid operators in handling an engine failure during take-off, design recommendations were made to help pilots identify which engine is a priority in a dual failure scenario and provide more information on the state of the engine damage (e.g., camera feed and strength of the impact; Parnell et al., 2021b).

SWARM will be used to investigate how systems can be designed to support operators in maintaining their SA using only digital information and their awareness of the automated system's state. The application of SWARM will also be used to generate training principles that could be used to train operators; however, it will first be important to consider the system's design to optimise the HMT's decision-making. Although SWARM was developed to analyse aeronautical decision-making, the PCM framework has been used to explore decision-making in other safety-critical domains, including uncrewed vehicle operations and other automated systems where the operators are operating a vehicle remotely or the operator's role is mainly supervisory (Banks et al., 2018a; Parnell et al., 2022), including in Chapter 3 to analyse a UAV accident. The SAW taxonomy only includes two specific references to aviation, so it can be easily adapted to apply to the maritime domain (Plant, 2015).

## 4.2 Method

### 4.2.1 Participants

Eleven participants took part in the SWARM interviews. Table 4.1 shows the key demographics of the participants. Due to the infancy of MASS and therefore a limited number of operators, the participant recruitment criteria also included participants without direct operational experience, but they knew about the development of current and future systems. Four of the participants had knowledge of MASS development, trials and certification and the other seven participants had direct operational experience.

Table 4.1 – Key participant demographics. (\*one participant had a significantly higher number of operational hours so was excluded from the average number of operational hours)

<b>Gender</b>	Male	9
	Female	2
<b>Age</b>	Average	41.82
	Range	21-68
<b>Years of Maritime Experience</b>	Average	18.68
	Range	2.5-40
<b>Participant Type</b>	MASS Operator	7
	Subject Matter Expert	4
<b>Number of operational hours for the operator participants</b>	Average (n=6)	288
	Range (n=6)	180-600
	Operational Hours* (n=1)	50,000

### 4.2.2 SWARM Interviews

The interviews were conducted in person or on video calls using Microsoft Teams, which was used to record and generate transcripts of all the interviews. Transcripts were checked, amended as necessary and anonymised by the researcher. The completed transcripts were then qualitatively analysed using the data analysis software Nvivo 12.

Before starting the interview, participants were given background information about decision-making for MASS operations and the Human Factors challenges surrounding their remote operation,

as well as an overview of the study procedure. Next, the interviewer gave the participants an explanation of the PCM and how it can be applied to investigate an operator’s decision-making process. A use case shown in Figure 4.1 was then described to the participants of an uncrewed MASS conducting an environmental survey of a coastal area using a lawn mower pattern and that the MASS was being operated from an RCC. The use case was given to the participants to provide a basis for the interview as some participants had no direct experience operating a MASS, and it is a fairly common MASS use case (Barrera et al., 2021; Devaraju et al., 2018). Then, the SWARM interview was conducted, in which the participants were asked the SWARM prompts in Table 4.2 along with additional follow-up questions as needed to gain insights into how they made their decisions.

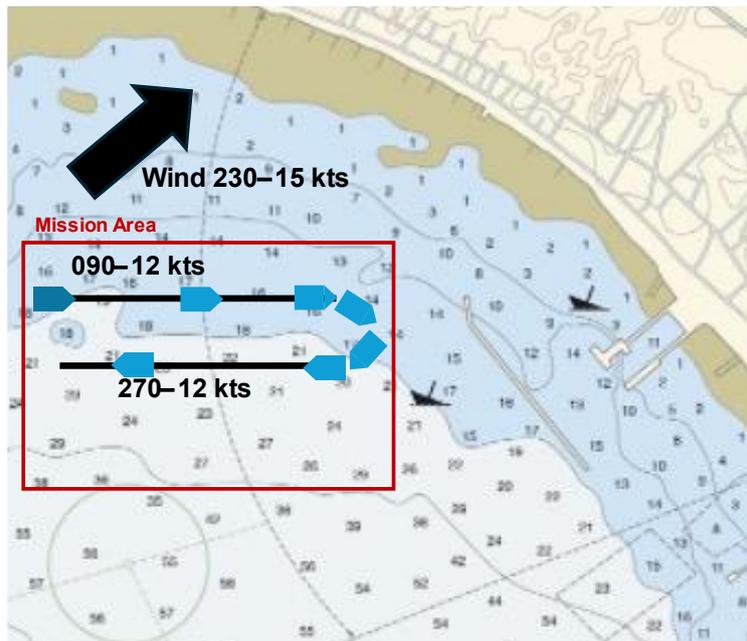


Figure 4.1- Use case diagram for an environmental survey using an uncrewed MASS being operated from an RCC.

Table 4.2 – SWARM prompts selected for the interviews (Plant and Stanton, 2016a).

SAW Theme	SWARM Prompt
Schema	<ol style="list-style-type: none"> <li>1. Does this use case remind you of anything you’ve read or heard or been involved in?</li> <li>2. Would you draw on previously acquired knowledge of similar MASS or other uncrewed vehicle operations?</li> <li>3. Could you draw on previous experiences of similar situations of conducting a survey? (if yes, what)</li> <li>4. Would your previous direct experiences influence you? (if yes, how)</li> <li>5. What pre-existing training that you’ve had might be useful in this case?</li> <li>6. What information would you know to be true or were you certain of? (Why?)</li> <li>7. Would you create a mental image in your mind to assist you? <ul style="list-style-type: none"> <li>• (If yes) What information (mental and/or physical) would you utilise to do this?</li> </ul> </li> <li>8. Would you imagine the consequences of your actions? <ul style="list-style-type: none"> <li>• (If yes) Would this impact on or change the decision/actions that you made?</li> </ul> </li> </ol>

Action	<ol style="list-style-type: none"> <li>1. Thinking about the use case – what would the main actions be?</li> <li>2. What information (mental and/or physical) would you be most useful or you would use to assist with your actions?</li> <li>3. What navigational actions might you take?</li> <li>4. What information (mental and/or physical) would you use to help you navigate?</li> <li>5. Would you communicate with anyone? (If yes, who to / what would be communicated?)</li> <li>6. In relation to the technological system, what would you be looking at (observing or checking) during the use case? What information would be essential to include?</li> <li>7. In relation to the physical environment, what might you look at (observe or check)?</li> <li>8. What were the key decisions might you make?</li> </ol>
World	<ol style="list-style-type: none"> <li>1. What artefacts would you have available to you? (e.g. physical objects, equipment, written documents, etc.)</li> <li>2. What information from the technological system(s) would you utilise/be most useful?</li> <li>3. How and where would you get this information?</li> <li>4. Might you receive information from others and how would you receive this information? (If yes, what)</li> <li>5. What could the communicated information tell you?</li> </ol>

### 4.2.3 Data Analysis

The SAW taxonomy (Plant and Stanton, 2016b), shown in Table 4.3, was then used to code the transcripts to explore the relevant factors involved in MASS operators' decision-making for each PCM component. The taxonomy was adapted for MASS operations to replace references to aviation with MASS instead. One code, 'Non-natural environmental conditions', was added to describe other environmental conditions such as other vessels, navigational lights and markers. The interview transcripts were also reviewed for passages where participants described specific incidents where they had to respond to abnormal situations or technical issues with the MASS; these passages were then analysed using the PCM framework to show how these incidents were resolved. The SAW coding results were then grouped into themes within each code, and design principles were generated for each of the 27 codes found in the transcripts. To assess the reliability of the SAW coding, inter-rater reliability analysis was used with two raters who were given 104 text segments from the SWARM transcripts, approximately 20% of the interview data. An average of 68% agreement was found, which resulted in a discussion between the raters, and a consensus was agreed to reach a percentage agreement of 80%. MASS status and display indications codes were rated differently as often the status of the MASS was determined by using the display indications and other codes such as environment monitoring and system monitoring were also clarified as when the operator is remote they monitor the environment via the cameras and display indications rather than a physical environment.

Table 4.3 - SAW Taxonomy adapted for MASS operations (Plant and Stanton, 2016b), see Appendix B for the full taxonomy definitions. (Note: asterisk denotes adjusted or added theme.)

Schema Themes	Action Themes	World Themes
Analogical Schema	Operate*	Absent information
Declarative Schema	Communicate	MASS status*
Direct Past Experience	Decision action	Artefacts
Insufficient Schema	Environmental monitoring	Communicated information
Trained Past Experience	Navigate	Display indications
Vicarious Past Experience	Non-action	Location
	Situation Assessment	Natural environmental conditions
	Standard operating procedure	Non-natural environmental conditions*
	System Interaction	Operational context
	System Monitoring	Physical cues
		Severity of problem
		Technological conditions

## 4.3 Results and Discussion

### 4.3.1 SAW Coding

Table 4.4 shows example quotes for each of the codes in the SAW taxonomy and the frequency of reference of each SAW code. The SAW category with the highest number of references was World (53% of the total references), followed by Action (32%) and then Schema (15%). Figure 4.2 shows the results of the SAW coding for each sub-category. The top overall six SAW codes with the highest number of references were 'Display Indications' (n=105), 'Artefacts' (n=86), 'System Monitoring' (n=74), 'Natural Environmental Conditions' (n=56), 'Navigate' (n=55) and 'Operational Context' (n=55). The Schema codes with the most references were the 'Declarative Schema' and 'Direct Past Experience' codes (21% and 17% of the total schema references respectively). In the Action category, 'System Monitoring' and 'Navigate' codes had the highest number of references (24% and 18%). The World codes with the highest references were the 'Display Indications' and 'Artefacts' codes (34% and 30%).

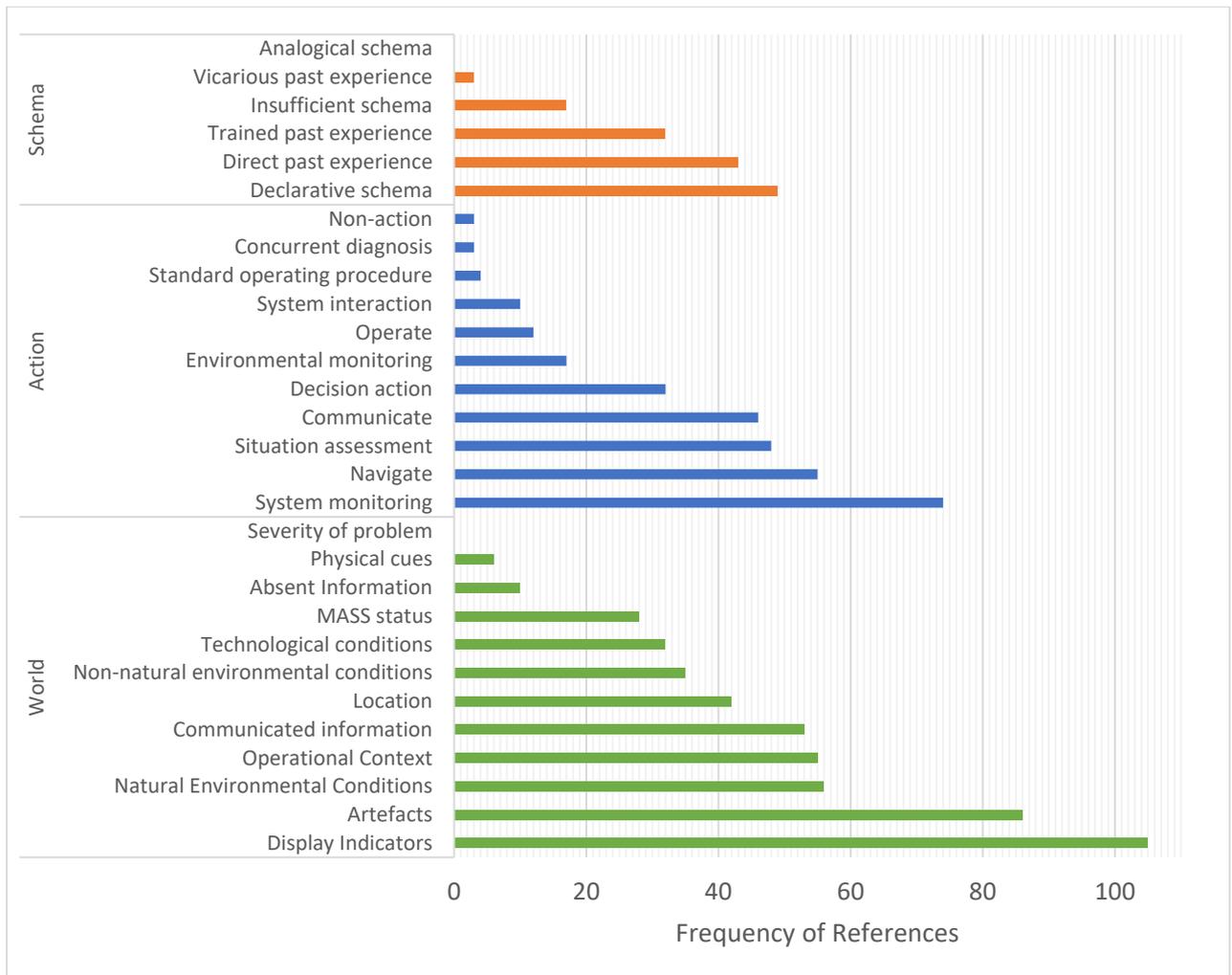


Figure 4.2 - Frequency of reference for each SAW code in the interview transcripts.

Table 4.4 - Frequency of reference to each SAW code in the interview transcripts and example quotes for each code.

SAW Code	SAW Category	Frequency	Example Quote
Display Indications	World	105	<i>"So we have our wind speed, we have our heel, and we have our roll and everything. We have all that put on like visible angles to understand the roll of the vessel."</i> (P11)
Artefacts	World	86	<i>"You might want to have a document that the user manual for the MASS might be handy so you can quickly look and see what it's supposed to be doing. Did I mention communications equipment, so VHF to have to talk to other vessels."</i> (P6)
System Monitoring	Action	74	<i>"If the monitor if the operator's monitoring it and everything is as it should be, they shouldn't need to take any navigational actions. It's about sort of I suppose it's just monitoring to see if it is following the path that it was projected to follow, and if it isn't, understanding when they might need to correct it and whether that correction needs to just be a you were supposed to be at this bearing, but we have a stronger inward current, you know that is putting all my bearings off by 2 degrees."</i> (P8)
Natural Environmental Conditions	World	56	<i>"If it's quite heavy sea state and it's near the limits of operation, then it might be causing the vessel to roll quite a lot which might be affecting your swath coverage of what you're picking up on the sea bed."</i> (P5)
Navigate	Action	55	<i>"Making sure that you're not getting yourself into a situation you can't get out of so with the limitations of the vessel in your mind that your sailing somewhere where you're gonna be able to sail out of essentially. So if you're coming into the coast making sure that you come in at a safe speed so that you can then make the turn to come back out and you're not gonna run into the shallows or anything like that."</i> (P10)
Operational Context	World	55	<i>"Surveyors like we've missed a patch here. You need go back here or this line was wonky do it again that type of thing."</i> (P7)
Communicated Information	World	53	<i>"You're also got the surveyor in your ear telling you to do things to make sure the survey data increases"</i> (P10)
Declarative Schema	Schema	49	<i>"...if I dropped the Revs below 25% and I alter the course to 180 degrees, she goes into manoeuvring mode so she, I'd expect her to alter round quickly with small turning radius."</i> (P11)
Situation Assessment	Action	48	<i>"But it's just that kind of interpolation, so you can see the draw on the batteries and you can see the charge in the batteries. So if you can see that the draw was too much for the batteries to have any charge going into them"</i> (P11)
Communicate	Action	46	<i>"I mean we use VHF to communicate back to the Coast Guard or whoever in Belize and Dominica. We would tell them we were, so we talked about Belize, we were, we moored in the harbour."</i> (P1)

Chapter 4

Direct Past Experience	Schema	43	<i>"Yeah, I mean taking actions to avoid collision and all of these sorts of things that I mean, that's still exactly the same as it always was, you're just applying it to basically to maybe like a different sized vessel you know, counting for, as I said, like depth of field with cameras." (P10)</i>
Location	World	42	<i>"I don't think there are any other environmental constraints. Um practically it, it's not particularly happy in the Caribbean." (P1)</i>
Non-natural Environmental Conditions	World	35	<i>"...being able to know that you're in a buoyed channel that you're going in the right side of a buoyed channel and that just because other vessels are in the buoy channel doesn't mean they're gonna hit you..." (P7)</i>
Decision Action	Action	32	<i>"If it was an overtaking situation or whatever, and then most likely options is we just come to a stop cause cause we're not, we're not big, we're not fast we can unless the vessel is gonna like collide with us at that point" (P11)</i>
Technological Conditions	World	32	<i>"what you gonna do when the vessel, if the when the vessel. If the vessel were to um to lose communications or breakdown. What you going to do that sort of line of shore is quite high cliffs. So are there going to be any blind spots in the radio communications" (P2)</i>
Trained Past Experience	Schema	32	<i>"Navigation side but also the you know the belly pack we used on the training course, it was basically the same one for line of sight operations so that definitely helped me get the upper hand and been able to actually, you know, follow a line which was good" (P7)</i>
MASS Status	World	28	<i>"Cause if that could dies, that's then the vessel will sort of go into it's it's emergency procedures, whether it's navigating to location, to stand by, whether it's stopping where it is." (P10)</i>
Environmental Monitoring	Action	17	<i>"Fishermen in canoes...Now they don't have AIS, they don't have radar reflectors and that they're the same colour as a White Horse, really. So they're not just not very visible. Um and practically I think we detected those more by looking at the path of the vessel than through the camera." (P1)</i>
Insufficient Schema	Schema	17	<i>"Having said that there was an area off Dominica which where the word it was relatively busier and there were large recreational yachts going between islands...there we kept out of the way as opposed to giving way because we weren't really sure how they would react to autonomous vessels." (P1)</i>
Operate	Action	12	<i>"Whereas on the joystick if you put the joystick all the way forward which would put 100% which can overheat the engines. If you got the azipod and main thruster on." (P11)</i>
System Interaction	Action	10	<i>"It has a has a route follower, there's a route following mode built in, so we we click that and it follows the route for us" (P11)</i>
Absent Information	World	10	<i>"You don't have any of the physical feels that you do on a conventional vessel, you don't have the sound, you don't have the, the motion of the vessel. You don't have, you can't sense vibration. You don't have any of these things that you can understand. What the vessel is doing if it's like if the vessel's unhappy." (P11)</i>

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Physical Cues	World	6	<i>"By far, the strangest one, is taking a when you're on board a vessel, you have the sea, the waves, the swell, all that you understand how the vessel's moving and its limitations. When you're taken from that physical feeling that you can kind of you understand to the reading different units on a screen and you're looking at the camera, which is a totally different perspective." (P11)</i>
Standard Operating Procedure	Action	4	<i>"You should have checklists for all the equipment how you start it up, how you maintain it, how you make sure it's functioning properly, all these sorts of things." (P10)</i>
Concurrent Diagnosis	Action	3	<i>"let's say the example of an engine failure. If a boat isn't going at the right speed. There's either something external that means it's not going at the right speed, or there's something internal that means it's not going at the right speed. If it's something in if, if I have looked at my environment and I have used the information to say actually the weather conditions, the current conditions, the wind conditions are as expected, I don't think it's something external there needs for me to be away from either me personally as an operator or someone with that level of skill to be able to diagnose if there is an internal issue." (P8)</i>
Vicarious Past Experience	Schema	3	<i>"It's where we're at now, we're able to layer experience. So like the guys, that have been in this job for a year, they can tell us so many things that they had to figure out in the first year. And now we can all work together and build on that experience cause everything's constantly changing." (P11)</i>
Non-action	Action	3	<i>"You go well I don't need it's always an alarm we don't check that cause it's always an alarm. But has anybody physically checked and see that the Hatch was closed or looked at the engine to make sure that there's nothing actually wrong with that temperature sensor. You know that the exhaust gas temperature you get sort of lulled into that, but it's alright. It's always like that. It's fine." (P10)</i>
Severity of Problem	World	0	
Analogical Schema	Schema	0	

### 4.3.2 Design and Training Principles Results and Discussion

Design and training principles for decision-making were then generated from the SAW sub-types and associated transcript data. The principles for MASS operators' decision-making were in four main areas, which each encompass different PCM sub-types across the Schema, Action and World components of the model. These key areas were derived from the transcript data and design principles associated with the SAW sub-type transcript data. The design principles were reviewed iteratively to look for themes to create the four key areas. Table 4.5 shows two example interview quotes for each key area, the relevant SAW code for the generated design/training principles and the frequency of quotes that supported the principle (for further examples, see Appendix C).

#### 4.3.2.1 Developing expectations of the automation

The first key area focused on the operator's ability to develop expectations of the automation. The design and training principles for supporting the development of appropriate automation expectations are shown in Figure 4.3. The principles show the considerations for supporting schema development, the types of world information required and the actions that will need to be supported. The key PCM components, in this case, were the display indications that the operator had available (World), the direct past experience or trained past experience of operating MASS in an operational scenario to develop expectations of the system (Schema) and monitoring the systems and automated navigation and assessing the situation (Action). For operators to be able to work within an HMT, they require a good understanding of what they can expect from the automated systems, allowing them to anticipate its behaviour.

For the world component of the PCM to understand the automated system, operators will need clear indications of key system information such as the automation mode, the health status and system parameters (e.g., speed and heading). This key information can then be used by the operator to determine whether the information meets their expectations. The operators highlighted that they need sufficient feedback from the automated system and a clear indication of the mode of key systems. Similarly, when operating other highly automated systems, mode confusion has been seen where the operator thinks the automation is in an alternative mode (Endsley, 2017; Silva and Hansman, 2015). This confusion can be more apparent in systems where there are multiple levels of automation for the system, which is expected in the operation of MASS (Endsley, 2017; Silva and Hansman, 2015). This was also seen in the UAV accident analysed in Chapter 3.

Table 4.5 – Example design principles for each of the four key areas, with example interview quotes and the number of related quotes.

Key Area	Design Principle	SAW Code	Frequency	Example Quote
Developing expectations of the automation	Clear indications of the automation mode, MASS health status, the functioning of individual systems, key MASS parameters and if any sensors are not receiving current data	Display Indications/ Artefacts/ MASS Status	42	<i>“The operator would need well it would be useful for them to have a display of the of the system parameters to so they can monitor the system's operating within those within these bounds so. You know, in terms of the endurance and any other aspects of the actual system itself.” (P4)</i>
Supporting the operator’s supervisory role	Extensive navigational experience and knowledge of relevant regulations for collision avoidance and navigational constraints for the areas of operation	Direct Past Experience/ Trained Past Experience	18	<i>“On the anti-collision side there is a very laid down international regulations for prevention of collisions at sea, so internationally recognised that all Mariners use essentially when they're, you know, when at sea operating a craft. So I would assess that they would need a thorough understanding of anti-collision regulations. Like I would driving a ship for example as a crewed asset, you would need to understand the rules for interactions between craft.” (P4)</i>
Supporting the operator’s ability to process digital information	Training and experience to get used to the limitations and difficulties in using cameras to judge speed, distance and to monitor the environmental conditions	Display Indications/ Artefacts	17	<i>“You’re only expecting 0.1 metre swell. But you look at the window on the boats all over the place and it's clearly not 0.1 metres, so it's definitely the cameras for the weather. Is the most obvious one that you I can't see you whether it's, you know 0.6 or 0.7 metres but I can see we're higher than 0.1 metres that was expected and you can see okay we're rolling around a lot more, we're getting very close to our limits type thing.” (P7)</i>
Supporting the operator’s supervisory role	Awareness of the other vessels in the area including giving operators access to general and local information sources such as, port movements list to allow them to develop expectations of the types of vessels and traffic density they might encounter	Non-natural Environmental Conditions/ Location	16	<i>“If it were looking at the vessels that around you looking at those looking at you know different sources, so AIS or the radar, port movement list, that kind of thing going OK, right? I'm expecting to see a such and such vessel. Is it here? Yes, there it is. And just sort of understanding of what's going around you because there is so much information that sort of it's just trying to bring all together and just form a picture of what's where you are and then what the immediate your immediate operating environment is actually like and what's going to be impact you? Are you bothered about the ship that's passing sort of 10 miles away, no probably not.”</i>

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				<i>Little fishing vessel was heading straight at you, something more to be sort of wary of.” (P2)</i>
Developing expectations of the automation	Training and experience in assessing and recognising when the operator needs to intervene/take manual control and considering the risks associated with their decided course of action	Situation Assessment	13	<i>“it's understanding what would happen if you did lose. And are there any other mitigating measures you can put into place? And if you're having some sketchy comms, do you carry on going? Towards that Cliff. Or do you go? I think I might stop here before something goes wrong.” (P2)</i>
Supporting the operator’s ability to process digital information	Provide additional information to account for lack of ship sense, e.g., the sea swell, the waves which gives the operator an understanding of how the MASS is moving	Absent information/ Physical Cues	10	<i>“You don't have any of the physical feels that you do on a conventional vessel, you don't have the sound, you don't have the motion of the vessel. You don't have, you can't sense vibration. You don't have any of these things that you can understand. What the vessel is doing if it's like if the vessel's unhappy.” (P11)</i>
Handling system faults and recovering the MASS	Training on when to make decision such as stopping the survey due to the health of any of the MASS systems	Decision Action	9	<i>“So is the actual vehicle working as expected? And if it's not, you may have to terminate the survey. So that's a key decision. And then is the payload behaving as expected. And if not you, you'd want to terminate the mission and correct that. Is the communications with vessel working appropriately or not? Depending on the level of autonomy you're expecting, some operator interaction you would need that communication link to be established, and again, if it's not, then you would probably want to terminate the mission.” (P6)</i>

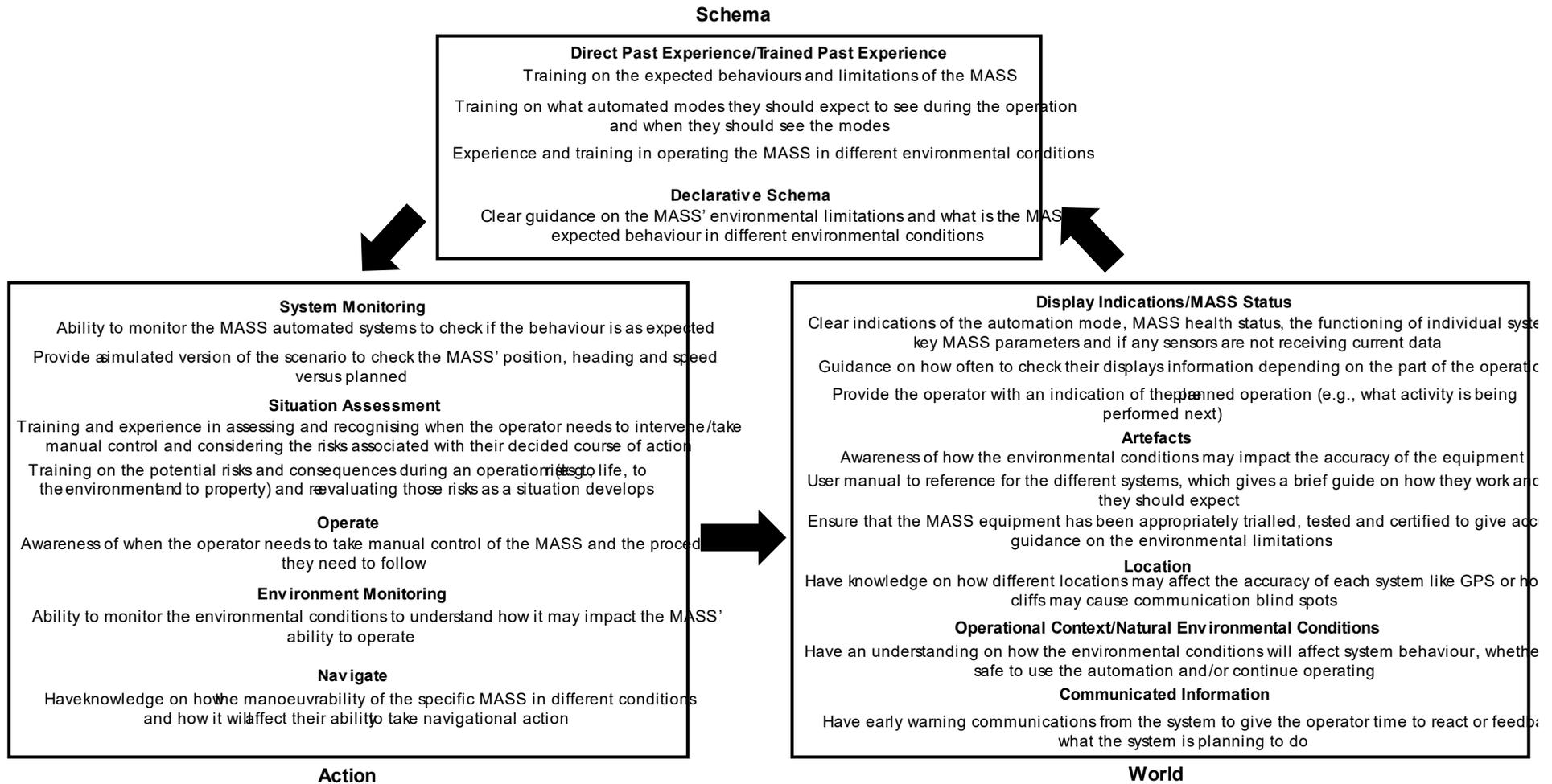


Figure 4.3 - Design principles to aid operators in developing appropriate expectations of the automated systems.

Another world principle was giving operators guidance on how often to check their displayed information, which would depend on the type of system and the context of the operations. Guidance on the monitoring would help to aid operators in forming accurate mental models by maintaining their SA and their ability to evaluate the automated system's behaviour against their expectations. The results showed the operator's reliance on world information; therefore, system transparency should be carefully considered so operators can easily interpret the system and determine whether it matches their expectations of the automation. This supports Kristoffersen's (2020) suggested guideline for automation transparency to support SA at an RCC, as it demonstrates the operator's need for transparency on what the automation is doing to give the operator a necessary level of understanding. For example, in the interviews, it was suggested that displaying the pre-planned operation (e.g., what route the MASS is expected to follow and the order of tasks it is expected to perform) would help the operator understand the MASS' behaviour. Similarly, Veitch and Alsos (2021) suggested automation transparent features such as path planning would allow operators to see how a MASS is planning to avoid another vessel so operators can create a mental model. Although operators should not need to know the detailed inner workings of the automation to be able to anticipate its behaviour, therefore these features should only include key information (Veitch and Alsos, 2021). This finding is similar to the principle that operators should have access to a user manual that contains a brief guide on how a system works to aid them in forming declarative schema but not overwhelming operators with too much detail on how the system works.

Whilst the highest proportion of the SWARM data is related to world information, it will still be important to support the operator's schema development so that they can recognise from the world information that the automated system's behaviour is not as anticipated. To support the schema component of the PCM, it was discussed in the interview that it would be necessary to ensure that operators have time and experience with the system to develop an appropriate schema of operations. This experience would aid an operator's ability to interpret the information from the automated system and to understand what actions to take. Although one principle was that artefacts should be fully tested before being deployed and certified by the relevant authority, which is currently an issue as MASS are novel. It has been shown that having prior experience with an automated system can influence their acceptance of that system, including systems that use higher levels of automation (Bekier and Molesworth, 2017). This suggests if MASS are not sufficiently tested and certified, it could lead to lower levels of acceptance if an operator has prior experience with an unreliable system. Operators' initial perceptions of the automation could affect their expectations of the automation; it has been shown that having lower initial expectations can have a more enduring effect on their future use (Barg-Walkow and Rogers, 2016).

For the operator's actions, the handover of control between the operator and the automation will be a key part of how effectively the HMT can operate and maintain system safety. The results showed that operators will need training in how the automation works and what they should expect from the automation so they can determine when a behaviour is unexpected, and they may need to take control. Similarly, it has been highlighted that there is a need to consider the training of MASS operators for high-stress situations such as unanticipated handovers from the system and that current guidance does not include the role of human users and interventions when working with automated systems (Tam et al., 2021). Automation training has been shown to be effective in other domains, such as automated driving, where drivers training on takeover requests from the automated system improved takeover performance, as suggested in the developed principles (Hergeth et al., 2017; Krampell et al., 2020).

Training on the automated system's limitations and strengths will allow MASS operators to develop appropriate mental models of the system and calibrate their trust (Drexler et al., 2018; Tam et al., 2021). However, there is a need to consider how this type of training should be delivered as a greater emphasis on the automation's strengths can lead to automation complacency and overconfidence in the system (Singer et al., 2022). Demonstration-based training could be used to support the training principle for giving operators training on the systems behaviours and limitations. It could be used to give operators a more detailed knowledge of the automated system's decision-making, and event-based training in a simulator would allow operators to gain experience interacting with the system (Fleming and Pritchett, 2016).

However, it has been shown that designing automation training for unreliable automated systems can be challenging as it has limitations in reducing complacency and automation bias (Sauer et al., 2016). However, Krampell et al. (2020) showed that training drivers meant they were more likely to take control in critical scenarios, as they had developed mental models for these situations and they were more able to recognise the situational cues. The developed training program included training elements to support the formation of declarative schema through the knowledge of the limitations of the system (Krampell et al., 2020). Similarly, MASS operators will need to be aware of environmental limitations and have schema developed in their training to create a mental model of the anticipatory cues for those takeover control scenarios. The level and type of training required for MASS will also be dependent on the type of system and its complexity. The operators will need sufficient training to develop schema for the different critical scenarios so they can recognise the cues and respond effectively (Meštrović et al., 2024).

### **4.3.2.2 Supporting the operator's supervisory role**

The second key area, shown in Figure 4.4, was supporting the operator's supervisory role. The design and training principles included having multiple information sources for the location of the MASS and

the vessels surrounding the MASS (World) to be able to monitor the situation and maintain oversight of any automated navigational systems (Action) and developing navigational experience for collision avoidance (Schema). A MASS operator's role will be predominantly supervisory, where the operator will be monitoring the automated system to provide a backup and intervene as needed. The principles highlighted the need to support system monitoring and navigation of the MASS, ensuring operators have sufficient navigational experience and the necessary information to maintain their SA and verify the information.

A key design principle was considering how the MASS operators' tasks will be designed to support them in monitoring the systems for long periods, an existing issue in the maritime domain (Cham et al., 2021). The introduction of higher levels of automation in MASS could make this effect greater, and it has been suggested that it could reduce an operator's takeover performance, perception and SA (Cheng et al., 2024a; Tam et al., 2021; Young, 2021; Young et al., 2015). In the design of MASS systems, it may be necessary to give the operator secondary tasks to reduce this effect by increasing their cognitive load and keeping them better engaged, this approach has already been effective in the automated driving domain (Cheng et al., 2024a; Gold et al., 2018; Mishler and Chen, 2024). Additionally, adaptive automation could be used to overcome cognitive underload, where the system can give manual control to the operator or a lower level of control to reengage them in the task (Byrne and Parasuraman, 1996; DeGuzman et al., 2022). Also, systems could be designed to adapt to the operator's state and give the operator tasks to manage (Byrne and Parasuraman, 1996; DeGuzman et al., 2022).

Another design principle was giving the operator an indication of the system's next actions, which would increase the system's decision-making transparency. It has been suggested that indicating a system's next actions is important for collision avoidance to allow the operator to collect information on the system and evaluate its functioning. This type of transparency could also support the operator in monitoring other tasks, such as the survey equipment deployment and survey progress (Ramos et al., 2019; van de Merwe et al., 2022b).

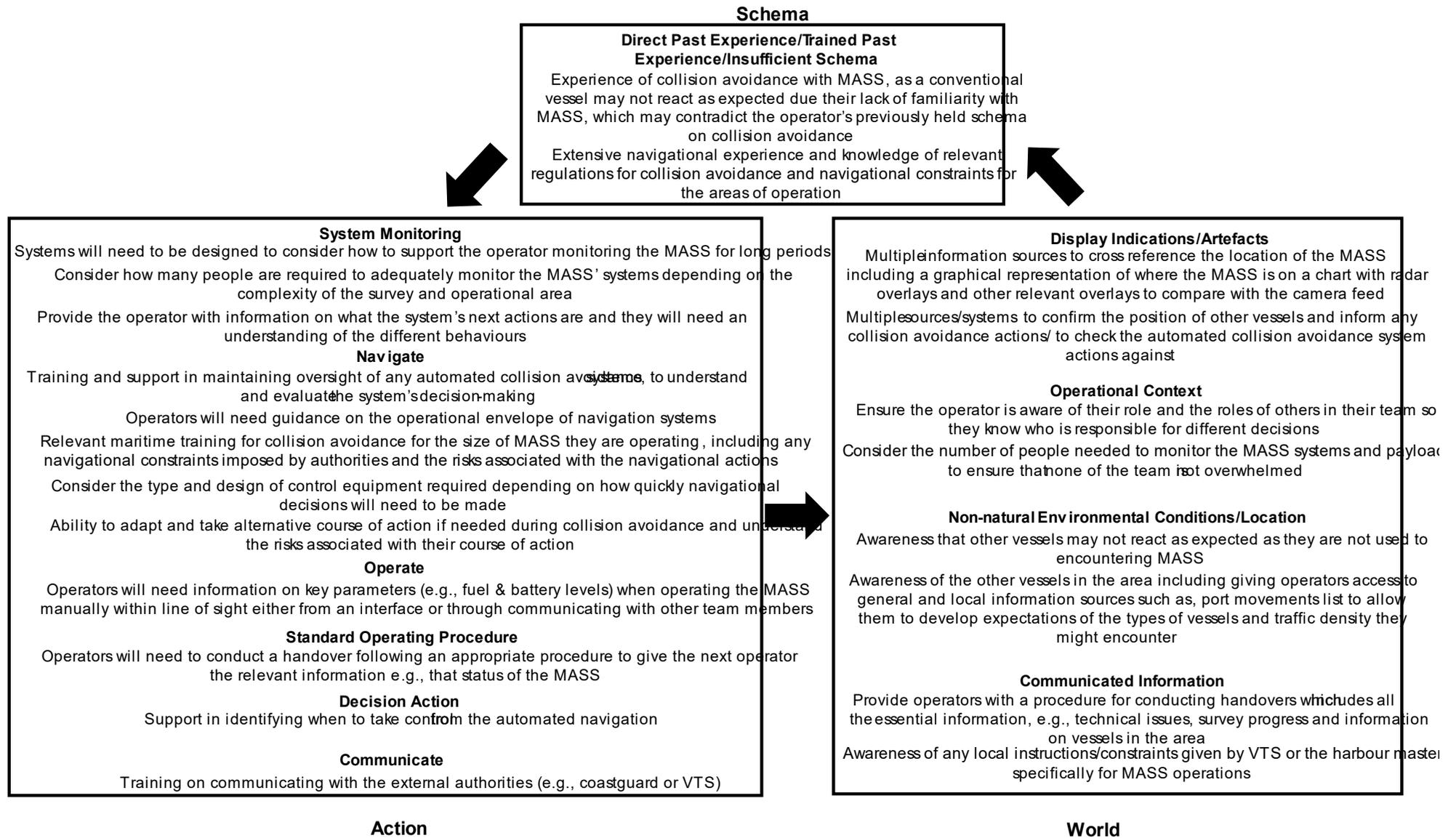


Figure 4.4 - Design principles to support operators in monitoring the automated systems, particularly the navigational systems.

Using animations or a trial function has been suggested to increase transparency in automated collision avoidance manoeuvres, to show the predicted outcome of the manoeuvre and to increase an operator's understanding of what the MASS is planning to do (Madsen et al., 2023). The identification of the target ships, the COLREG rule being followed, and a reason for why the system had decided on the manoeuvre (e.g., type of ship, aspect) could also be used to support the design principle for giving the operator an indication of the system's next actions (Madsen et al., 2023). Increasing the transparency of a collision and grounding avoidance system has been shown to improve SA, although no effect between transparency and cognitive workload was found (van de Merwe et al., 2024). The type of information to gain system transparency was also important; the users preferred to have information about the system's analytical information (e.g., objects that posed a collision risk and intended paths; van de Merwe et al., 2024). However, it was unclear which level of transparency gave the best performance; it may be that the transparency needs to be adjusted to the individual user, further research should investigate other levels of system transparency for collision avoidance (van de Merwe et al., 2024).

One of the training principles in the schema category for supporting the operator's supervisory role was ensuring that operators have advanced navigational training. It has been shown that having onboard experience in navigating a vessel can improve a novice operator's navigational ability versus an operator with no onboard experience, even though they understand the collision regulations (Hwang and Youn, 2022). Similarly, setting navigation routes and updating system configurations for a navigation route has been identified as a risky task in MASS operations due to their complexity and the risks of collisions with other vessels (Liu et al., 2022b). However, to support operators in monitoring collision avoidance, their world information will be key to them being able to perceive the situation correctly and check the system is making a safe and optimal decision. Therefore, operators will need multiple sources of navigational information to cross reference and be able to form their mental model.

The findings have also highlighted that operators will need specific experience with MASS, particularly in situations where conventional vessels react unexpectedly during a collision avoidance manoeuvre due to their unfamiliarity with MASS, leading to potentially dangerous and confusing situations. Standard operating procedures will be needed for handover between different operators to ensure the new operator has all the information they require, including the automated system mode. However, it has been seen that additional standard operating procedures may be required to ensure that the automated functions are being utilised effectively (Roberts et al., 2021).

### 4.3.2.3 Supporting operators' ability to process digital information

The third key area for decision-making was the ability to process digital information (Figure 4.5); that is, the ability to develop SA through solely digital information from the display indications and technological conditions (World) and to have time to get used to monitoring the information and assessing it (Schema and Action). Figure 4.5 shows the design and training principles that were generated from the SAW subtypes for operations from an RCC, including the additional world information that will be needed and supporting operators in performing actions remotely. When operating MASS uncrewed, one challenge is the lack of physical cues to interpret when making decisions. Key design principles for supporting the operator's ability to process digital information were providing the operator with multiple sources of information to aid their decision-making and providing alternative forms of feedback to replace the lost physical cues. Various types of sensors and systems will be needed to replace the physical cues, as each will have limitations, which was a concern of many of the mariner participants.

It will be important to consider how this additional information is given to the operator, as current user interfaces predominantly rely on visual information. The use of mostly visual information could cognitively overload the operator, so it will be necessary to design the information around the specific goal of the operator for their tasks in addition to the appropriate mode of the information (Kristoffersen, 2020). Kristoffersen (2020) recommended engaging with users who have experience with conventional vessels to ensure that the information they are provided with is sufficient to replace their sensory information and that they still have high levels of SA. It has been shown that 3D and virtual reality HMIs can improve a MASS operator's SA when compared to a conventional desktop-based HMI (Lager et al., 2019). These types of technologies could be used to help overcome the issues associated with remote operations and support the design principle for display indications in providing information to the operator to replace their physical cues, although there are various human factors considerations which need to be investigated further (Kazemi and Lee, 2023; Lager et al., 2019).

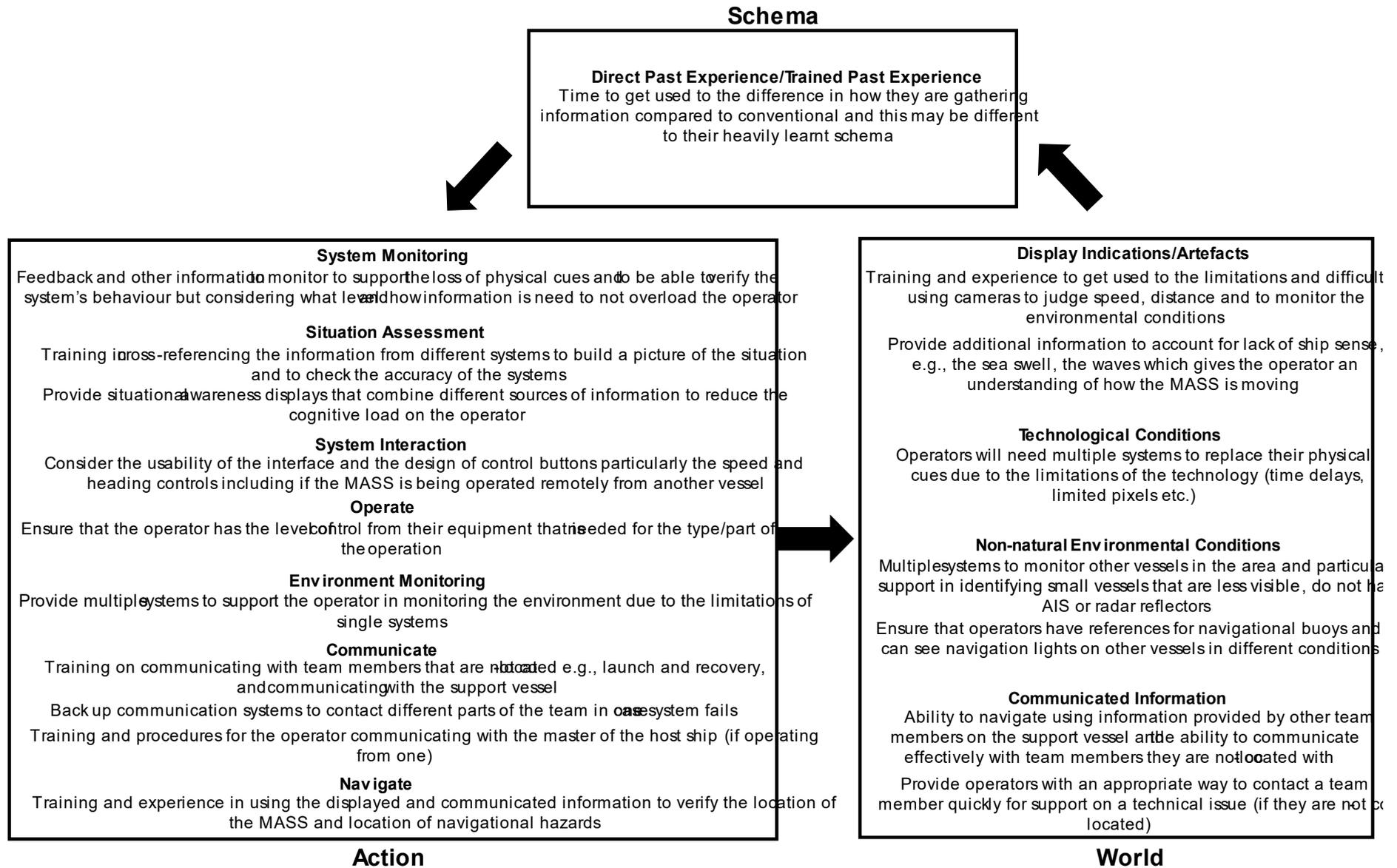


Figure 4.5 - Design principles for supporting operators' ability to process digital information.

The usability of the interface and the types of controls selected for the RCC will be important factors, especially if the MASS is being operated on a host ship, as this could make interacting with the interface more challenging in harsher environmental conditions. The usability of the operator's interface is a key consideration, as it can affect the operator's SA and workload (Nielsen, 1994).

Another training principle is that operators will need experience using alternative sources of information from the technological systems to maintain their SA and make effective decisions. Similarly, a design principle was that additional information is needed through their display indications to replace their physical cue information. It has been found that conventional navigational instruments were given low usability scores when used in an RCC rather than on a conventional bridge (Karvonen and Martio, 2019; Man et al., 2018b). When traditional instruments were used at the RCC, the operators found that it was more challenging, as verification was more difficult, and they had to use additional tools (e.g., camera feed and radar) to compensate (Man et al., 2018b). This suggests interfaces will need to be redesigned for RCCs to reflect the differences in how the system is being operated and support the operators' ability to gather information.

The operators will also need experience in using alternative sources of information from the technological systems to maintain their SA and be able to make effective decisions, but it will be important to also consider the usability of the HMI designs to reduce the training burden and make gathering the information more intuitive. However, due to this difference in the type of information they will use, operators will need training to practice how they will gather the information and develop new schemata (Kristoffersen, 2020). Developing new schema for remote operations may be difficult for them due to operators' heavily learnt schema from their mariner training and experience in how they would normally verify information from technological systems with physical cues before making a decision.

#### **4.3.2.4 Handling system faults and recovering the MASS**

Lastly, Figure 4.6 shows the fourth key area of handling system faults and recovering the MASS, the design and training principles included that the operator will need information on the condition of the system and guidance and artefacts to support them in diagnosing system faults (World), experience of these types of system faults occurring (Schema) and guidance on the diagnostic and recovery actions they need to perform (Action). Operators will be responsible for handling system faults, understanding the impact of the fault on the operation and making decisions on when to recover the MASS to the host ship or shore.

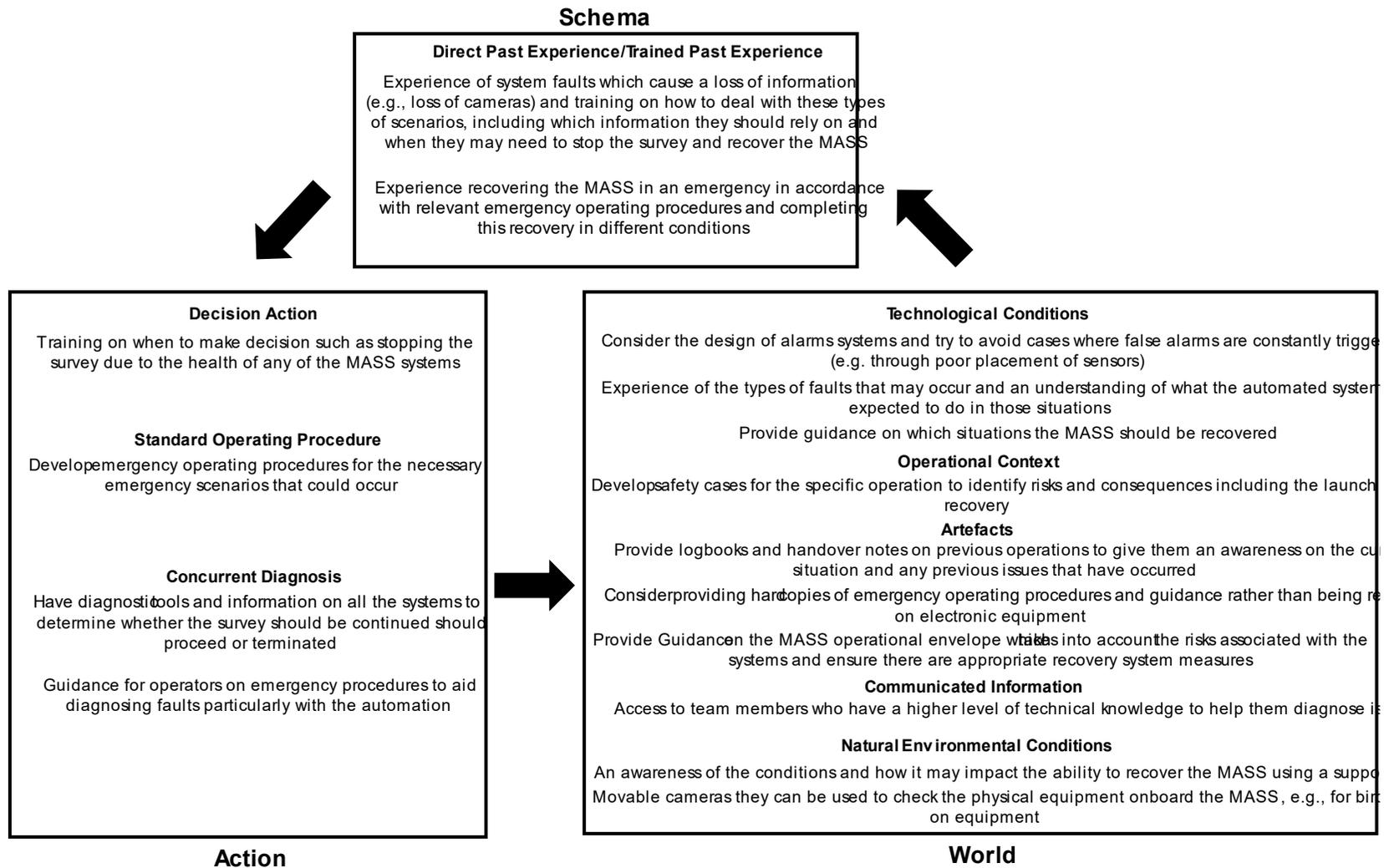


Figure 4.6 - Design Principles for aiding operators in handling system faults and recovering the MASS if required.

Early warning systems could be used to get the operator's attention if there are any anomalies in the MASS' behaviour or if there is a system fault (e.g., a sensor stops functioning). The design of the alarm systems for the automation will need to be carefully considered to alert operators, and guidance has already been suggested for similar systems such as automated vehicles (Mehrotra et al., 2022). It will be necessary to consider the use of multimodal alerts, how the alerts can be designed for a smooth transition between levels of control and whether the intensity is appropriate for the urgency of the alert (Mehrotra et al., 2022). Early warning systems and other assistance systems will also be needed to aid operators in regaining their SA before taking over from the automation and optimising takeover performance (Cheng et al., 2024a). However, monitoring issues such as automation-induced complacency will need to be considered to reduce the potential for out-of-the-loop performance problems, where operators may fail to monitor automated systems adequately, and they could miss system failures, particularly when they are operating highly reliable systems (Wickens et al., 2015). It has been shown that in training, when operators have experienced automation failures, they are less likely to show complacency behaviours (Bahner et al., 2008). This suggests that operators may need to experience training scenarios with different types of failures to reduce the likelihood of complacency (Bahner et al., 2008).

The types of diagnostic tools and information provided to the operator at the RCC will also be important to support their concurrent diagnostic action. Han et al. (2022) discussed the potential to overload the operator when monitoring systems such as the engine room, as more information will be sent from the MASS; due to limitations of current sensor systems, multiple sources will be needed to replace the lack of physical cues. To mitigate the risk of information overload and poor comprehension when monitoring the engine room remotely, Han et al. (2024) investigated the importance of different cues within the engine room to understand which cues are needed to activate the appropriate schema. It was suggested that rather than providing all of the possible information to the operator, it is necessary to focus on displaying only key information that will activate the correct schema for that situation (Han et al., 2024). Future work could explore using SWARM to understand the key cues for various system fault scenarios and suggest design recommendations.

Operators will need training on handling different system faults and failures to gain experience in what other information to utilise in these cases, as they may have lost the information they would normally use (e.g., camera feeds or AIS data). It has been highlighted that more research is needed on training operators to respond to automation-related anomalies and to improve automated-related operator performance in aviation, and similarly for MASS, further research is needed to understand how future operators should be trained to work with automation (Strauch, 2017). In addition to training, operators will need emergency procedures that cover various scenarios to

support them in responding quickly and effectively. In addition, they will need training on troubleshooting, as the automation failures may be complex and unpredictable, and therefore, they may need to be adaptable (Schaafstal et al., 2000). Logbooks and handover notes, which include the faults and issues that have been experienced, would provide the operator with guidance on what could be expected. These artefacts would also give operators an opportunity to learn vicariously, allowing them to develop mental models for the types of issues they may see during their watch.

### **4.3.3 General Discussion**

The findings further demonstrate that the SWARM can be used to generate user-centred design recommendations in a domain beyond aviation. It has been highlighted that engaging with users will be important in the design and development of future MASS systems to ensure operators have the necessary information and systems are designed to optimise their decision-making (Kristoffersen, 2020; Vu and Lützhöft, 2020b). This application of SWARM has shown its utility when developing future designs as it can be used before a system and the end users exist to generate design and training principles. It is a useful approach for system designers as it shows what and how the key world information is used by operators to form their mental models and, therefore, needs to be included in the system design.

Other applications of SWARM have investigated aeronautical decision-making for the design of an engine monitoring tool for a bird strike, a system for engine oil leaks and aerodynamic stall events (Banks et al., 2021; Parnell et al., 2021b; Sturgess et al., 2024). These applications of SWARM were also used to identify key operator tasks and generate design and training recommendations to support decision-making (Banks et al., 2021; Parnell et al., 2021b; Sturgess et al., 2024). Sturgess et al. (2024) also showed that SWARM can be used to generate various training recommendations. Similar to Sturgess et al. (2024) trained past experience was found to be key in the operator's ability to recognise and make appropriate decisions, like in aerodynamic stall events, MASS operators will need training to be able to recognise key cues for different intervention scenarios. Another design principle that has similarities to previous applications of SWARM is providing the necessary diagnostic tools and information to aid decision-making in the case of system faults, Banks et al. (2021) suggested using a graphical representation of oil level data trends over time to aid operators in recognising subtle changes to oil levels.

Emergency procedures were identified as key to supporting operators taking action when responding to a fault, for an engine failure scenario on a future flight deck, it was suggested that the system could suggest relevant checklists for the operators to use, which could also be used in the design of future MASS systems (Parnell et al., 2021b). However, as SWARM was applied to a general operational use case for MASS in this case, higher level design principles were generated rather than

more specific design recommendations as in the other applications of SWARM. Although, applying SWARM to a general operational use case in this case rather than a specific event has demonstrated that initial design and training principles can be suggested before more in depth analyses can be conducted with users or SMEs on specific use cases. In addition, not having existing users and a system design in novel domains like MASS, the specifics of their operation may not have been defined.

Due to the infancy of MASS, a small sample size was used, and some of the participants did not have operational experience, although they had extensive knowledge of how MASS are and will be operated in the future. Future work could investigate the decision-making of a larger sample of operators to explore more challenges that have been experienced in MASS operations, including any future critical incidents, to understand why they occurred and how they were recovered.

Similar to other applications of SWARM a lower presence of schema data was found within participants' responses (Plant and Stanton, 2013a; Plant and Stanton, 2015; Plant and Stanton, 2016c). This is a limitation of the SWARM interview technique is the challenge in eliciting schema data, which could explain the lower number of schema references as mental models are often triggered unconsciously, so participants may not be able to articulate schema data as easily as world and action data (Plant and Stanton, 2013a; Plant and Stanton, 2015; Plant and Stanton, 2016c). Although there were fewer references to schema it is still important to consider how the world and action components of the PCM influence the operator's schema. Whilst training principles have been suggested to aid operators in the development of appropriate schema, the design principles suggested for the world and action components will be key in ensuring that appropriate schema is triggered as demonstrated by the cyclical nature of the PCM. Therefore, the design principles from the world and action categories will also indirectly support schema as well, as designing systems that are compatible with operators' mental models should aid their decision-making, in addition to considering their training requirements. Further work could investigate operator's decision-making in real-time by using verbal protocol analysis with operators who are operating in a real-world or simulated scenario, as there are also limitations in using recall methods. Future work could also apply SWARM to specific decision-making events, such as a particular system fault or failure to investigate how to support decision-making in a particular scenario. However, the decision-making design and training principles developed here have identified initial areas that need to be considered during the design of MASS systems training of future operators, and it will be necessary to understand how these principles can be applied through further research.

## 4.4 Summary and Conclusions

SWARM interviews with MASS operators and SMEs have been used to develop design and training principles to consider for optimising operators' decision-making. The design and training principles support the three components of the PCM framework, schema, action and world, across four key tasks in MASS operation. The key tasks identified were evaluating the automated system's behaviour against their expectation, supervising the automated systems, operating remotely without physical cues, and handling system faults.

For developing appropriate automation expectations, the design principles were around the world information, display indications, artefacts and the environmental conditions that the operator can utilise to evaluate whether the information matches their expectations or whether they need to take action and intervene. Therefore, it will be necessary to consider the system's transparency to aid understanding and reduce the potential for mode confusion (Endsley, 2017; Kristoffersen, 2020; Silva and Hansman, 2015; Veitch and Alsos, 2021). Additionally, it will be important to consider the operator's training requirements to support the development of appropriate schema when interacting with the automation (Drexler et al., 2018; Tam et al., 2021). For optimising operator performance in supervising the automated systems and especially navigation, the design principles considered cognitive underload (Cheng et al., 2024a; Young, 2021; Young et al., 2015) and the system's transparency, as operators will need relevant information to understand and evaluate the system's reasoning (Ramos et al., 2019; van de Merwe et al., 2022b).

For operating without physical cues, design principles were suggested, including the need for multiple systems to provide further information to aid operators in maintaining their SA (Kristoffersen, 2020; Man et al., 2018b). There will also be a need to consider the system's usability when exploring how that additional information might be displayed (Karvonen and Martio, 2019; Man et al., 2018b). Lastly, for handling system faults and recovering the MASS principles, consider the design of alert systems and diagnostic tools to optimise the operator's performance and to give operators experience in handling system faults so they are more able to recognise these situations (Cheng et al., 2024a; Han et al., 2024; Mehrotra et al., 2022; Strauch, 2017).

Further research should explore how these design principles could be applied in the design of future MASS systems and how the training principles could be incorporated into the training syllabuses for future operators. In the next chapter, trust will be explored as it is a factor identified within the decision-making factors in HMT model. Similar to this chapter, in Chapter 5, trust will be investigated using the PCM framework by applying the Trust variant of SWARM. This approach will be used to investigate how systems can be designed to aid operators in forming calibrated trust.

# **Chapter 5 Principles for engendering trust in human-machine teams: exploring Maritime Autonomous Surface Ship operators' trust using the Trust-Schema World Action Research Method**

## **5.1 Introduction**

To extend the findings in Chapter 4, where design and training principles were generated for MASS operations to support decision-making, this chapter aims to understand the key factors involved in informing a MASS operator's trust. Trust is being investigated because it has been identified as a key factor in the decision-making factors in HMT model, which was found to be strongly influenced by transparency in the development of the initial model in Chapter 2. The Trust variant of SWARM developed by Parnell et al. (2022) was also used in the interviews conducted in Chapter 4. Like SWARM, Trust-SWARM also utilises the PCM to underpin the interview schedule, but the prompts are focused specifically on trust. The results of these interviews have been analysed in this chapter to generate design and training principles for forming calibrated trust within the HMT. The findings will also be used to extend the decision-making factors in HMT model in Chapter 2 by further investigating the factors that influence trust in an HMT. It is demonstrated that operators will need support to be able to evaluate the automation's behaviour and the digital information that is replacing their physical cues to understand when and how much they should trust the system.

### **5.1.1 Trust challenges in operating MASS**

With the advancement of technology leading to higher levels of automation being used in MASS, there are potential trust implications as MASS operators will adopt a predominantly monitoring role (Dreyer and Oltedal, 2019; Gregor et al., 2023). At these higher levels (three and four; see Chapter 1 for the full definition of these levels), the operator will be less involved in the decision-making process, and it may be more difficult to achieve calibrated trust, where the operators' trust matches the system's capabilities (Karvonen and Martio, 2019; Man et al., 2018b). Another challenge for trust within the HMT is that MASS may be operated uncrewed, where the operators are no longer onboard the ships but are relocated to an RCC (Karvonen and Martio, 2019; Wahlström et al., 2015). It has been suggested that operators may be uncertain of how trustworthy the systems that replace their physical cues will be (Gregor et al., 2023; Palbar Misas et al., 2024). The operators' trust could

then affect their ability to maintain their SA, as they could lack the relevant knowledge of the state of the environment and the automated system (Sanders et al., 2011).

Trust is, therefore, a key determinant for the perceived impact of future MASS (Chan et al., 2023; Mallam et al., 2020). Trust may affect the operator's use of and reliance on a system, for instance, an operator may choose not to engage the automation or use its full capability if they believe the systems are not trustworthy (Lee and Moray, 1992; Lee and See, 2004; Matthews et al., 2020; Parasuraman and Riley, 1997). Underutilisation of automated systems has been found in the Royal Navy for a variety of systems due to users' lack of trust (Barrett-Pink et al., 2019). Conversely, trust could cause an overreliance on automated systems, which has been seen in various maritime accidents (Marine Accident Investigation Branch, 2014; National Transport Safety Board, 1997). Therefore, it is important to consider how MASS operators can achieve calibrated trust and not over or under-rely on the automation (Chen et al., 2018; Gregor et al., 2023).

There are different types of factors that may influence trust within a HMT (Hancock et al., 2011; Hoff and Bashir, 2015; Schaefer et al., 2016). It has been found that factors such as the system's transparency and reliability influenced the formation of calibrated trust (Bobko et al., 2023; Chen et al., 2018; de Rosa and Strode, 2022). An unreliable system has been shown to reduce operator trust, and operators may not accept the automated system, even if the probability of a system failure occurring is low (Chavallaz et al., 2016; Lee and Moray, 1994; Man et al., 2023; Manzey et al., 2012). Operators' training will influence their learned trust, and it has been highlighted that seafarers will need sufficient training to develop trust in future automated systems (Chan et al., 2023). It has been shown that calibration and coordination training can influence learned trust in HMTs in the operation of remotely piloted aircraft systems (Johnson et al., 2023).

### **5.1.2 Trust-Schema World Action Research Method**

The Trust-Schema World Action Research Method (T-SWARM) was developed by Parnell et al. (2022) to extend the SWARM interview technique using additional prompts focused on the decision-maker's trust. T-SWARM has been used to understand the dynamics of a UAV operator's trust by exploring their decision-making using the PCM and generating design recommendations (Parnell et al., 2022). The PCM has been used to investigate trust in human-machine interactions by exploring how a user's cognitive experience of trust is generated from the world information available to the user and whether it meets their expectations of the interaction, which then informs their actions (Parnell et al., 2022). Similarly, T-SWARM will be applied in this chapter to investigate how trust is built between the operator and MASS, what factors may damage trust and how trust can then be rebuilt.

## 5.2 Methods

### 5.2.1 Data Collection

The T-SWARM interviews were conducted in the same interviews as the SWARM interviews described in the preceding chapter, for a detailed description of the procedure and participants refer to sections 4.2.1 and 4.2.2. In the interview, the participants (n=11) were asked the T-SWARM prompts shown in Table 5.1 for each category of the PCM.

Table 5.1 - T-SWARM prompts selected for the interviews for each PCM category (Parnell et al., 2022).

SAW Theme	T-SWARM Prompt
Schema	<ol style="list-style-type: none"> <li>1. Can you recall a point in this situation when you did not (or might not) trust the MASS? <ul style="list-style-type: none"> <li>• Please expand on this situation and why you did not trust it</li> </ul> </li> <li>2. Would you generally trust the MASS? <ul style="list-style-type: none"> <li>• Please expand on why this is</li> </ul> </li> <li>3. Do you have any distrust in the MASS? <ul style="list-style-type: none"> <li>• What is the cause of this distrust? How could it be repaired?</li> </ul> </li> <li>4. Would you be wary or suspicious of the MASS at all? <ul style="list-style-type: none"> <li>• Do you view the MASS to be reliable/dependable? At which points in an operation would this be most likely?</li> </ul> </li> </ol>
Action	<ol style="list-style-type: none"> <li>9. What actions would you be relying on the MASS for?</li> <li>10. What actions would you not be relying on the MASS for?</li> <li>11. How easy would it be to trust the MASS to do their job?</li> <li>12. How could your trust in the MASS change over the course of the operation?</li> <li>13. Could there be any negative outcomes? <ul style="list-style-type: none"> <li>• And how would this effect your trust in the MASS for the future?</li> </ul> </li> </ol>
World	<ol style="list-style-type: none"> <li>6. Would you ever be uncertain about the reliability or relevance of the information that you had available to you?</li> <li>7. What information/knowledge would you need to trust the MASS?</li> <li>8. Could there be any deceptive information?</li> <li>9. What information would you need to repair any lost trust in the MASS?</li> </ol>

### 5.2.2 Data Analysis

The data analysis for this chapter used the SAW taxonomy to code the segments of the transcripts, which was used in the preceding chapter and detailed in section 4.2.3. The segments of the transcripts were coded to the relevant SAW themes to explore which themes were most relevant to the operator's trust in the MASS. Inter-rater reliability analysis using two raters was conducted, the two raters were given 76 text segments from the T-SWARM transcripts, approximately 20% of the interview data, to rate against the SAW codes. The results of the analysis showed a moderate percentage agreement of 66%. A discussion was had between the raters to agree on a consensus to reach a percentage agreement of 80%. For example, codes such as insufficient schema, direct past experience and trained past experience had been rated differently as the participants were talking about operating a hypothetical system. Similar to chapter 4 MASS status and display indications were

also rated differently and system monitoring and environment monitoring. Next, the transcript segments were rated as *positive* (segments that described trust in the MASS/MASS system or how trust could be built), *negative* (segments describing lack of trust in the MASS or over-reliance), and *neutral* (segment was neither positive nor negative about trust). A scree plot was then used to analyse the SAW sub-types to identify which are key factors in MASS operators' trust to be able to generate design principles to support these key factors (Cattell, 1966). This approach has been used previously as a method to cut off data sets (Parnell et al., 2022; Parnell et al., 2016).

## 5.3 Results and Discussion

### 5.3.1 SAW Results

#### 5.3.1.1 MASS Operators' Key Trust Factors

Figure 5.1 shows the results of the scree plot of the SAW sub-types for MASS operators' trust, which was generated from the transcript data (Figure 5.1). The intersection fell on "MASS Status", so the seven factors above the intersection were considered: "Display Indications", "System Monitoring", "Technological Conditions", "Situation Assessment", "Artefacts", "Direct Past Experience" and "Navigate".

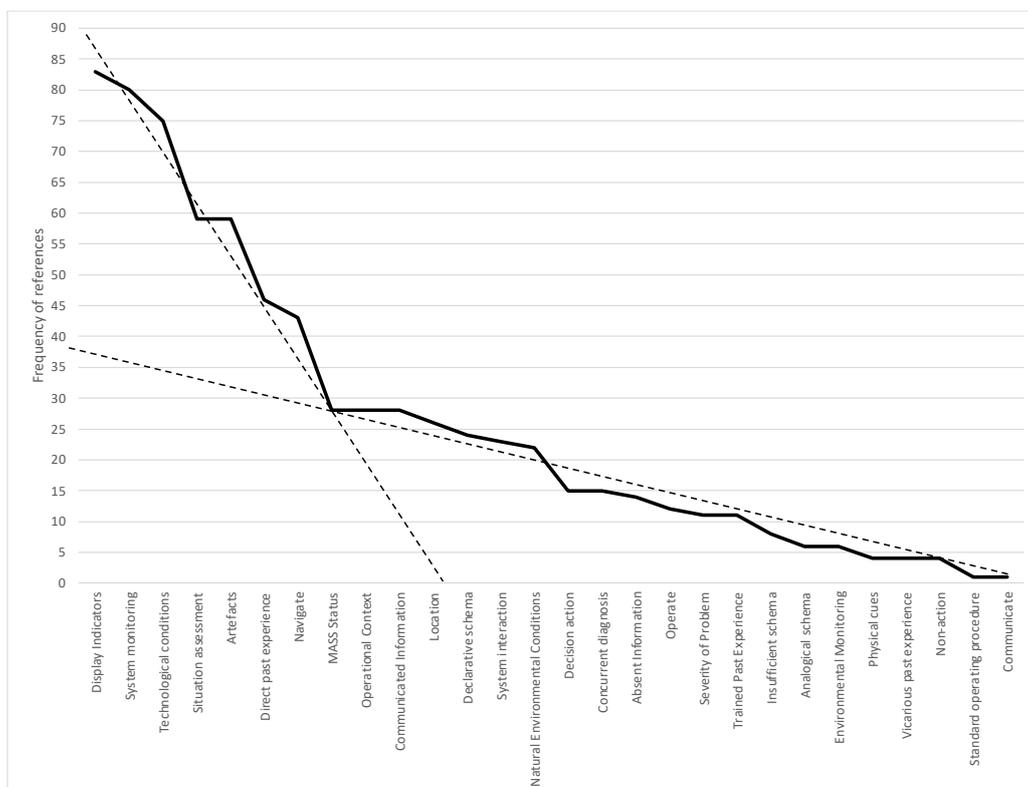


Figure 5.1 - Scree plot highlighting the most important factors when discussing MASS operators' trust.

The results for the number of references of each sub-category in the SAW taxonomy split by schema, action, and world are shown in Figure 5.2, while Table 5.2 shows the frequency of reference for each of the sub-categories with example quotes. The highest number of references was seen in the world category (51%), followed by the action (35%) and then the schema (14%) categories. There may have been fewer references in the Schema category as five of the participants had no individual experience of operating MASS, and MASS is a relatively new technology that has not yet been operated extensively. Figure 5.2 also shows the results of rating the SAW references as positive, neutral or negative to an operator’s trust. The World category had the highest number of negative references to trust (47% of the total world references), followed by Action (44% of the total action references) and then Schema (36% of the total schema references). Conversely, the Schema category had the highest percentage of positive references (49% of the total schema references), followed by Action (30% of the total action references), and then World (23% of the total world references).

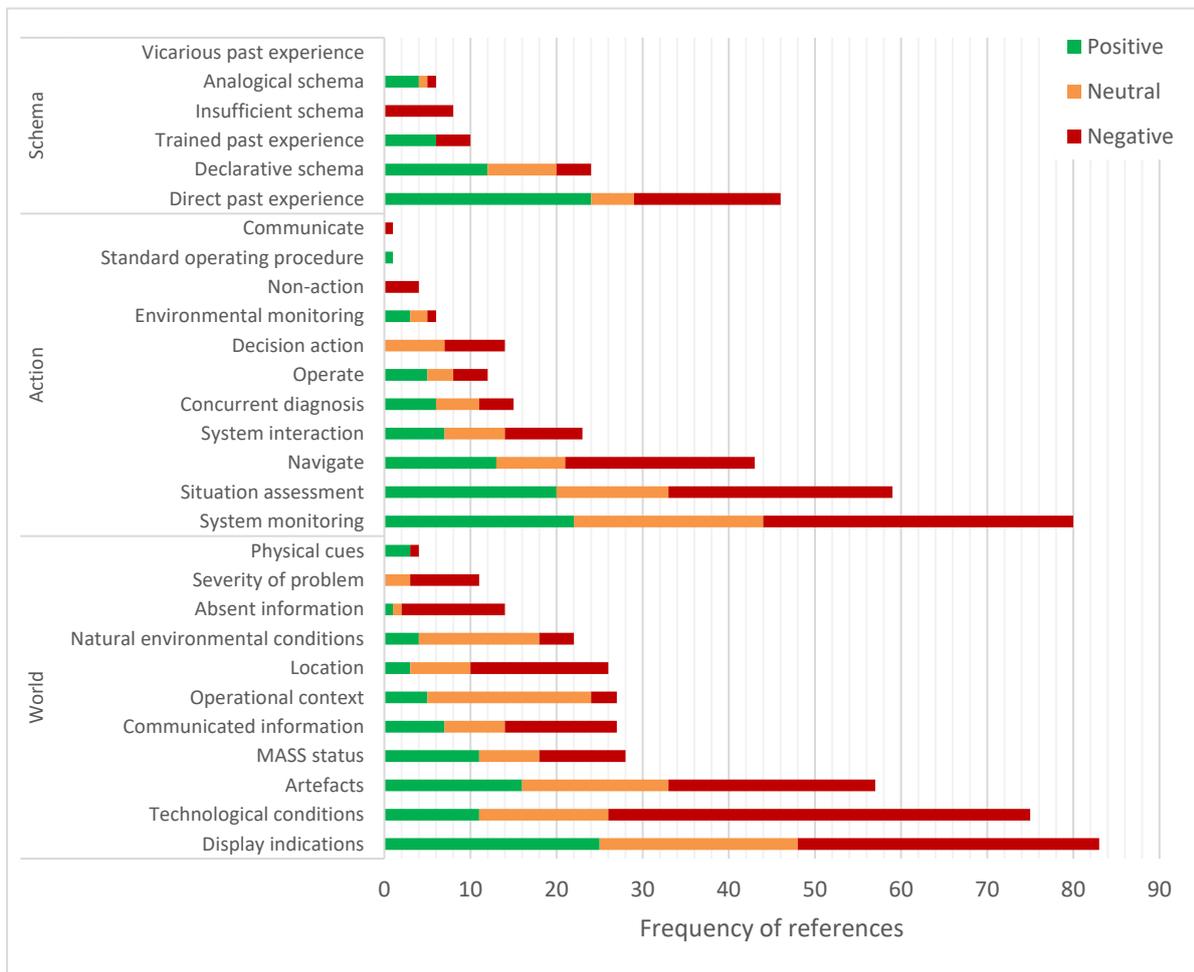


Figure 5.2 - Frequency of SAW code references rated as positive, negative or neutral responses to the operator’s trust.

Table 5.2 - References to SAW codes on trust during the MASS operation interviews.

SAW Code	SAW	Frequency	Example Quote
Display Indications	World	83	<i>"Some concept of how old this information is does at least give you an idea of whether it's valid or not..." (P3)</i>
System Monitoring	Action	80	<i>"If it's something simple like it drifts off course for no reason...Then for the rest of that, you're gonna be like, I don't know why it did that. You're gonna be watching it a bit more closely..." (P10)</i>
Technological Conditions	World	75	<i>"...GPS are in certain places in the Eastern Med...that position we'd be up to a mile out. So you know you cannot rely on it at all...it can be sort of 10/15/20 metres out..." (P2)</i>
Situation Assessment	Action	59	<i>"And does your echo sounder say that you've got 10 metres underneath you and you look at the chart and you go, the depth is 10 metres? Great. If the depth is 200 metres and your chart echosounders saying 10, then there's something wrong there." (P2)</i>
Artefacts	World	59	<i>"...passing through that anchorage, I didn't trust anything at all, and I was probably the most stressed I've ever been professionally. The cameras were useless..." (P7)</i>
Direct Past Experience	Schema	46	<i>"I think it reliability, dependability actually comes back... it's about the experience built up with the platform as a series of platforms." (P3)</i>
Navigate	Action	43	<i>"...every time I got on to navigating with a MASS I had no trust in it whatsoever, so I was constantly building my own trust in every decision that was made." (P9)</i>
MASS Status	World	28	<i>"...sometimes connection issues in between VSAT and 4G which causes a delay and causes a sometimes for the system to put her into position hold mode..." (P11)</i>
Operational Context	World	28	<i>"I think proximity and the amount of time, effort, money, etcetera is taken to get via asset to where it is and how difficult and costly that was will directly relate your tolerance level of failures of kit ..." (P5)</i>

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Communicated Information	World	28	<i>"...this is I guess to do with the information coming back from it, from the sensor, from the payload sensor and if it wasn't making sense you know, in our example before it was supposed to be seeing a pinnacle at this roundabout this time, and it wasn't seeing on... That would leave to distrust in what's going on out there, either in the payload or in the system itself." (P6)</i>
Location	World	26	<i>"So there's there were some electronics that bearing in mind that we were operating the Caribbean which over heated and it died." (P1)</i>
Declarative Schema	Schema	24	<i>"...she can take 3 metre waves her operational level is much lower than that because the as she rises and falls in the swell her VSAT becomes hidden from the satellite. So we have like sometimes connection issues in between VSAT and 4G which causes a delay and causes a sometimes for the system to put her into position hold mode ..." (P11)</i>
System interaction	Action	23	<i>"...I think it comes down to trust in the equipment that you're working with and if I put in a port helm order, I know she's going to port. If I put it astern and I know she's going to go astern so I would trust her to that extent..." (P7)</i>
Natural Environmental Conditions	World	22	<i>"Depends on the weather conditions... flat calm. Probably fairly easy, but the weather conditions increased...they would need to be stabilised because if you've got a rolling MASS...then you your visuals could be going up in the air and then down in the sea..." (P6)</i>
Decision action	Action	15	<i>"My choices were to sit and do nothing or keep going. So we just kind of we reduce speed to enough that I can you know very, very comfortably stop or you know turn..." (P7)</i>
Concurrent diagnosis	Action	15	<i>"I think you need you need one [indicator] which so everything you don't worry about it or amber one and then you obviously have to click on that and you say ohh it's my sensor gone or engines died or whatever, whatever it might be" (P1)</i>
Absent Information	World	14	<i>"So the AIS stopped working and that I was very much not trusting the vessel, so where she was like the location where she was fine, but very much not trusting the information she was sending back to me because everything else has stopped working..." (P7)</i>
Operate	Action	12	<i>"Obviously within line of sight if I'm actually, you know, on a line of sight operation. If I'm using the belly pack, then that's different because I can see. And I can see a lot more I can. I have a lot more situational awareness" (P7)</i>

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Severity of Problem	World	11	<i>"Yeah a significant cut out... very difficult to trust a vehicle at that point as to don't know when N is going to occur. And you don't know if N plus is going to be quite significant at which point... you can't trust that it will actually return and recover at distance." (P3)</i>
Trained Past Experience	Schema	11	<i>"...it needs training and I think that [the information about the automated system] could be introduced through some sort of simulation environment, simulated environment. So that people can understand you know, for instance, when it reaches the end of one search pattern and turns 180 degrees to do the next search line how fast it takes to turn. How quick it does the turn." (P6)</i>
Insufficient schema	Schema	8	<i>"So if I was to be given one today and told to go and use it. It wouldn't be easy for me to trust it at all, because I'd have no background information on whether it's been used in earnest and been successful or not." (P6)</i>
Analogical schema	Schema	6	<i>"It'll be like one of the new Teslas that drives along the road by itself but you still have to be holding the steering wheel in case it does something wrong. It has the potential to do it correctly and go along fine 99% of the time, but I mean that one time it doesn't." (P11)</i>
Environmental Monitoring	Action	6	<i>"And the other thing is environment so if you started off in a fairly benign conditions at the in the morning and then the wind picked up and then it started to get quite rough. I would be more suspicious about its reliability and dependability, so an awareness of the environment" (P6)</i>
Physical cues	World	4	<i>" ... when I'm doing line of sight I don't have the nav charts, I don't have radar or anything. I'm literally just doing it with what I can see and its fine I can totally trust it." (P7)</i>
Non-action	Action	4	<i>"And then there's the false trust or over trust because you're not really, you're not interrogating it very often. And it's just you're almost letting it just carry on and do its thing..." (P5)</i>
Standard operating procedure	Action	1	<i>"... you would constantly monitor the like the sound velocity in the water. If you're doing the bathymetric survey...it might be something procedurally you need to physically check every so often... that's just an operating procedure thing and just ensuring that you are and ensuring your kits calibrated and using the right parameters for that operating area..." (P4)</i>
Communicate	Action	1	<i>"But I think if you were to go into busier area, you'd be verging on the lines of like when I'm on a conventional ship, if I'm uncomfortable at any point in terms of not knowing what I'm doing or not knowing what another vessel is doing, we call the captain straight away." (P7)</i>

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Vicarious past experience	Schema	0	
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### **5.3.1.2 World**

#### **5.3.1.2.1 Display Indications**

The “Display Indications” SAW code had the highest number of references (11% of the total references), with participants commenting on how the information displayed at their RCC would influence their trust. A key concern for the operators was trusting the digital information since they are no longer able to verify that information using their senses and are now reliant on technological systems. The “Display Indications” sub-category had a high number of negative ratings (42% of its references); the participants had reduced trust when incorrect information was displayed or they believed that information was incorrect.

The participants discussed that their trust was reduced because it is more difficult to diagnose a system fault as a sensor could be giving a false reading, and a fault reduced their trust levels in other system information as well. However, there were positive references (30%) to trust, such as suggestions that spotter drones could be used to provide more visual references to help operators verify the information displayed to them and ensure that they have multiple sources of information available.

#### **5.3.1.2.2 Technological Conditions**

The participants' references to the sub-category “Technological conditions” were mostly negative concerning trust (64%) and had the highest number of negative ratings (15%) across all the world, action and schema categories. For example, many of the participants discussed different system faults that reduced their trust in the MASS, including communication issues which were unexpected and stopped the operator from receiving real-time information. In one case, a participant experienced reoccurring thruster and communications issues, which led to a significant loss of trust in the MASS as it occurred at random intervals, and no explanation for the issues could be found.

Other issues were experienced with large inaccuracies seen in the positional information, therefore affecting the operator’s ability to rely on it. Another operator experienced a problem with the AIS information, which made it more difficult for the operator to trust the rest of the navigational systems. The participants were also concerned about the cyber security risks of digital information being spoofed or denied, which could also impact their trust.

#### **5.3.1.2.3 Artefacts**

“Artefacts” had the third highest number of negative references (42% of the “Artefacts” references) in the World sub-categories. Participants lacked trust in the camera equipment due to their limited range on smaller vessels and the quality of their display equipment. Another issue was the lack of

regulations and standards for MASS equipment, which led to lower levels of trust, particularly in the navigation equipment. There were positive references (28%) in the “Artefacts” sub-category, it was mentioned understanding the factors affecting the different MASS systems (e.g., radars and camera systems), which therefore could affect the systems’ accuracy or reliability, would allow them to calibrate their trust. Some participants had high levels of trust in their equipment, such as track-following software and electronic chart plotters, as they found them accurate.

### **5.3.1.3 Action**

#### **5.3.1.3.1 System Monitoring**

“System Monitoring” was the most referenced SAW code within the Action categories. To be able to trust the monitored information, participants wanted to be able to cross-reference it from different sources. For the Action category, the highest number of negative ratings were found in the “System Monitoring” sub-category (45% of the “System Monitoring” references); some of the negative references related to not being able to effectively monitor the systems due to reliability issues. With increasing levels of automation, participants discussed the potential that operators might over-rely on the MASS systems and not monitor the systems effectively. In addition, if the MASS did something unexpected it would reduce their trust, such as deviating from the expected course without a known reason. The ability to monitor the systems in real-time would also improve their trust in the systems as they would have a more accurate view of the situation and to have a pre-planned operational display to monitor the progress.

#### **5.3.1.3.1 Situation Assessment**

Another key action of the operator is interpreting the information from the MASS systems and ensuring that they are aware of the MASS’ situation. Similar to “System Monitoring”, participants discussed their ability to maintain their SA through cross-referencing and interpreting the digital information available to them, to verify that information and ensure that their view of the situation is accurate. The “Situation Assessment” sub-category had a high number of negative references (44%), especially about evaluating the accuracy and reliability of the digital information the operator needs to maintain their SA. The participants mentioned that having multiple sources of information or having backup systems would allow them to understand which pieces of information they should use when assessing the situation.

#### **5.3.1.3.2 Navigate**

Their ability to effectively monitor the navigation of the MASS was an important action, as navigation is a primary safety concern and essential for survey accuracy. Participants wanted to have a high level of trust in the navigational information (e.g., radar and GPS) to have confidence in the MASS’

position and the location of any surrounding vessels. The negative references included concerns about navigation information accuracy, as when operating over the horizon, they were only able to verify the information with other forms of digital information. The participants were also sceptical about trusting automated collision avoidance systems for navigation due to the complexity and variety of the situations that could be encountered.

#### **5.3.1.4 Schema**

##### **5.3.1.4.1 Direct Past Experience**

The participants' experiences operating MASS and conventional vessels influenced their trust in the systems. For example, one participant had not experienced any system faults or unexpected behaviours when operating the MASS, so they trusted the systems in the absence of any reason not to. Similarly, other participants had positive experiences using MASS for surveys, with trust being built as they had more experience operating in different conditions. However, "Direct Past Experience" has the highest number of negative references within the Schema category (50%). Participants felt that it was not easy to trust the MASS but said this was no different to their trust in a conventional vessel's automated systems. Loss of communication with the MASS was mentioned by the participants, which reduced their trust as they were unable to monitor or control the MASS, and in some cases, this led to collisions with navigational buoys. However, experience operating a MASS within line of sight improved the participant's trust as they were able to understand how the MASS was reacting to the weather conditions.

#### **5.3.2 Design and Training Principles**

The transcript data from the top seven sub-types of the PCM and the four key areas previously identified from the SWARM interviews (see section 4.3.2) were used to inform design and training principles for trust. The four key areas were supporting the operator: in developing expectations of the automation, their supervisory role, processing the digital information and handling system faults and recovering the MASS. The design and training principles are shown in Figure 5.3 and Figure 5.4, using the PCM framework to illustrate how operators can be supported in forming calibrated trust in the automated system. For example, for operators to develop appropriate expectations of the automation, they will need to be provided with information on the limitations and capabilities of the automation (world). This information would then be used to determine if the world information meets their expectations (schema), which then would inform the actions they might take based on their level of trust. Table 5.3 shows example quotes that were used to inform the design principles for trust (for further examples, see Appendix D). The analysis of the top seven SAW codes and associated transcript data generated 41 design and training principles. Eighteen of these principles

matched with the principles developed in Chapter 4 (see section 4.3.2), which left 23 principles specific to trust that are shown in Figure 5.3 and Figure 5.4.

### **5.3.2.1 Developing expectations of the automation**

The results of the interviews showed that it will be important that operators understand the limitations and capabilities of the automated systems so they can develop appropriate expectations and reliance on them. Figure 5.3 shows the principles for developing these expectations through an awareness of the limitations and capabilities of the system. It has been found that in the Royal Navy, operators have not utilised several current automated systems due to their lack of trust in them, as they do not understand their full capabilities (Barrett-Pink et al., 2019). Similarly, when interviewing SMEs on the impacts of autonomous shipping, it was found that having an understanding of how the automated systems worked and how they made decisions would be needed to develop trust (Mallam et al., 2020). Transparency has been found to improve calibrated trust in HMTs by giving the user reasoning behind the automated system's decision in addition to notifications of what decision it had made, and it has been suggested this will be required for the design of automation for future bridges (Bobko et al., 2023; Man et al., 2023). This understanding could be achieved through experience of operating the MASS in different conditions and scenarios so that operators can develop appropriate expectations of the automated system (Parnell et al., 2022). Giving operators training on the limitations and capabilities of the automated systems could be used to promote calibrated trust; simulator and video training for highly automated vehicles has been shown to moderate drivers' trust and support accurate mental model development (Ebnali et al., 2019; Krampell et al., 2020). Trust calibration training has been found to reduce the impact of trust violations in the operation of a remotely operated aircraft, although it was not found to increase the detection of automation failures suggesting other approaches may be needed to improve operators' monitoring performance (Johnson et al., 2023).

Table 5.3 – Design and training principles example quotes and the number of related interview quotes.

Key Area	Design/Training Principle	SAW Code	Freq.	Example Quote
Developing appropriate expectations of the automation	Information on the capabilities and limitations of each technological system	Technological Conditions	12	<i>“I spent a lot of time not trusting the MASS, chart updates to the position, GPS is a big thing and the connectivity I was always concerned with connectivity that if you had a shadow or you went into a blind spot of a larger structure, you'd lose the connection and that's normal on a small ship, big ship no matter what signal balance, signal skip if you hit you hit an installation and the GPS signals were being bounced, you could be actually closer to it than you actually thought you were, or you could be further away from it and you actually were. So I did not trust at any stage, at anytime of my operation. However, I was saying the exact same thing, for my life at sea, I did not trust any system without a verification in my own head, that it was the correct one and that that was my way of managing safety.” (P11)</i>
	Ability to evaluate the navigational information based on the limitations of the equipment	Navigate	12	<i>You can't totally and utterly rely on it and it's the same as when you're navigating a ship by radar. But the big difference between that is when you're operating by radar, you can look out the window and go does the image I'm seeing on this reflect what I'm seeing out there...You've only got you're a AIS ranges probably about 6 miles max and your radars about the same. So you do you do fall into these limitations, so you've got to you got a cross reference things. You're checking that is there any AIS target where the radar target is and can I see a light when it comes into range you're trying to, you're trying to figure all these things out. But yeah, mostly you trust it.</i>
Supporting the operator's	Experience operating the MASS where it performs all its required tasks in an operational scenario	Direct Past Experience	14	<i>“Do the second run if it's starting to match up with any information that I've held previously, I'd be gaining good confidence now and probably when it did the next turn and started its third run. I'd probably be happy that it's doing what I what it's supposed to be doing so it's building up confidence over time I suppose in the system.” (P3)</i>

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supervisory role	The ability to monitor information in real-time or near real-time and ensure that operators are aware of the actions they need to take in the event delayed in transmission or communications failure	System Monitoring	4	<i>"I think the ability to monitor stuff in real time or near real time is quite important, because if you were to do a mission which takes I don't know 12 hours, 5 days, whatever it takes, and then you can't assess the successful collection of data or quality of a data until after you've finished. Then you could lose trust quite quickly, whereas if you can monitor it in real time or near real time and have confidence, but it's doing or collecting what you want it to do and that helps build trust in it." (P4)</i>
	For collision avoidance systems a clear indication of which object is being avoided and an explanation of what it is going to do and why	Display Indications	1	<i>"It comes up and gives you warnings, and so it tells you what the object is the same as what we talked about before, when it highlights something, it'll tell it will highlight that, and then it'll start to give an instruction to within the system. So you can see what it's doing and you can see why you can see kind of why it's done it because you know what object it's trying to avoid." (P10)</i>
Supporting the operator processing digital information	Multiple sources of information that can be cross-referenced to check the reliability of the systems	Artefacts	27	<i>"You can't totally and utterly rely on it ... so you've got to you got a cross-reference things. You're checking that is there any AIS target where the radar target is and can I see a light when it comes into range...." (P11)</i>
	Information from additional systems (e.g. a UAV) to provide an alternative view	Artefacts	4	<i>"I guess if you did have some visual on it, you could see whether it's heading north or east, that would help a lot. You could have a spotter drone, maybe that's providing the the plan view of what's going on in real time, you could you could have that collaborating your information and then you've got the information from the sensor as well." (P6)</i>

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<p>Handling system faults and recovering the MASS</p>	<p>Information on the types of faults that could occur and the potential consequences</p>	<p>Technological Conditions</p>	<p>12</p>	<p><i>“Everyone's kind of learning definitely. I wouldn't say I'm suspicious about it, but you yeah you have gotta be a certain level of suspicious about everything you're doing because like I said, the the information you can't 100% make sure that it's actually what's telling you you're doing and you can't you can't like if the engine temperatures spiking on a normal ship you phone up the engineer and go go and check the engine temperatures and he goes ohh the sensors broken or whatever, it's OK we're still fine. Whereas here you've got the kind of you gotta believe what's telling you, or understand why it's telling you that what the issue is.” (P11)</i></p>
	<p>Time after system failures to rebuild the trust in the MASS to complete the operation and an explanation of why it occurred</p>	<p>Direct Past Experience</p>	<p>4</p>	<p><i>“So if it's loss of trust because the platform failed continuously over a period of time, then again it's about building that trust through Ok, taking it out small trial smaller smaller trials, doing building up okay it is now up to an operational level in building it back up to to that to that aspect.” (P6)</i></p>
	<p>Understanding of the potential negative outcomes of different system faults</p>	<p>Situation Assessment</p>	<p>3</p>	<p><i>“And I think the same sorts of principles apply across onto the onto the MASS kit in terms of. Um, it depends on what an exit outcome is and what the consequences associated with that negative outcome are.” (P3)</i></p>

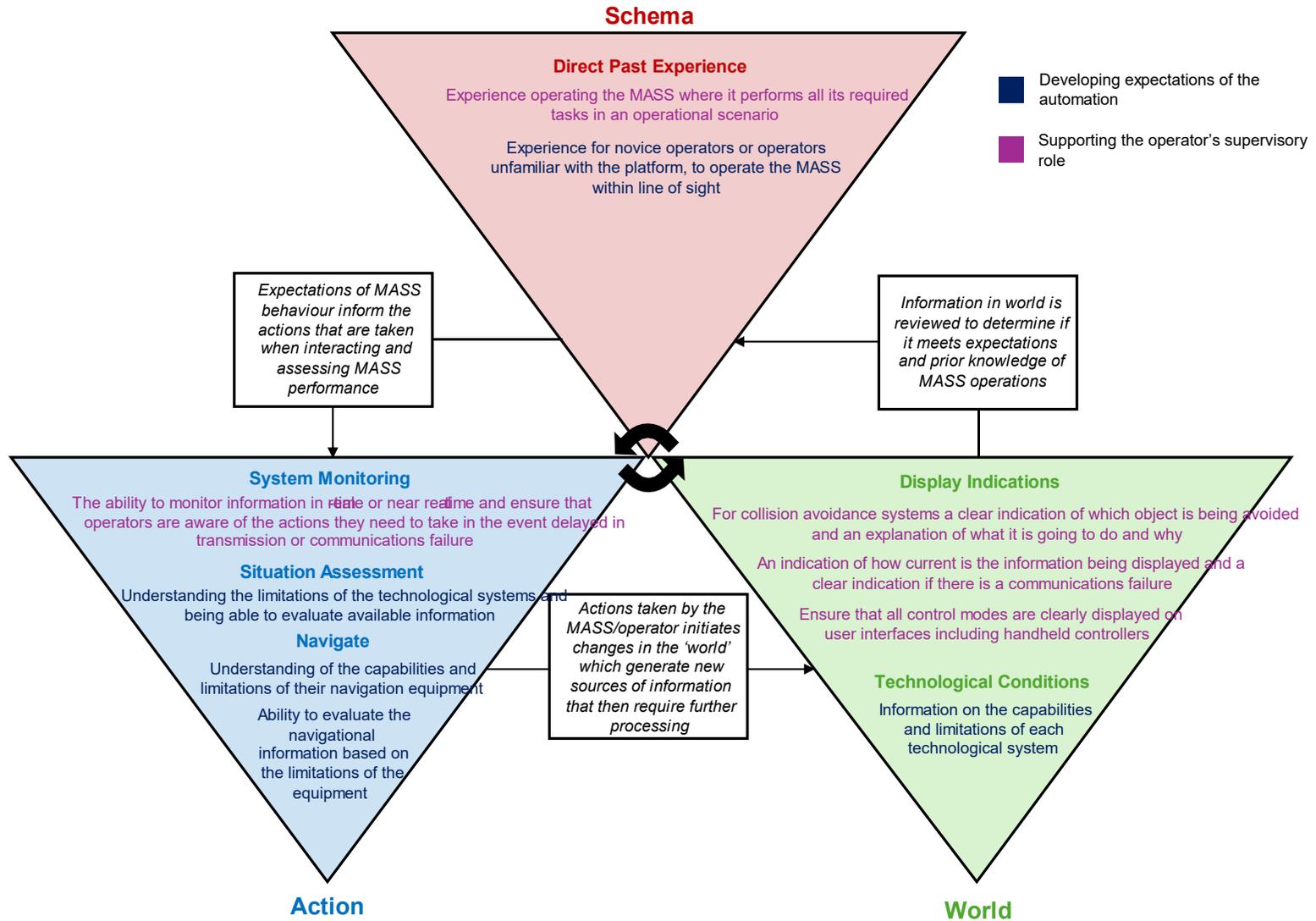


Figure 5.3 - Principles to support the operator in developing expectations of the automation and to support their supervisory role

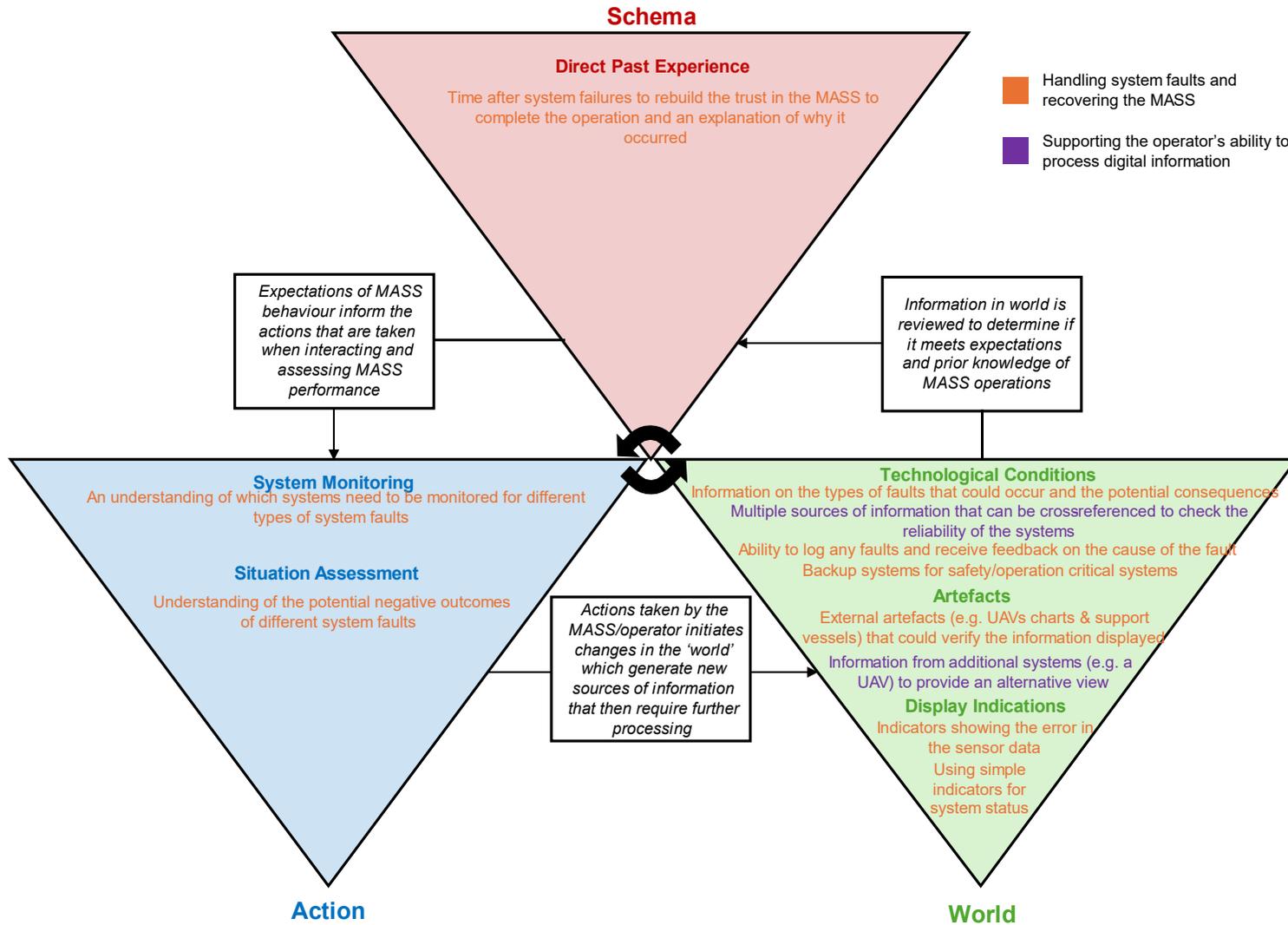


Figure 5.4 - Principles to support the operator's ability to process digital information and to handle system faults and recover the MASS.

It was discussed that some participants felt they would need to know how the MASS had been tested, and certified in the future when standards are developed for MASS by an appropriate body. The fact that the MASS has been certified to meet future standards would potentially increase their initial trust in the system. Pastra et al. (2022) suggested that for trust to be established in a sociotechnical system it will be necessary to consider ensuring that there are appropriate regulatory frameworks and guidance in the maritime domain, so that users and stakeholders can trust automated maritime systems. It has been suggested that a user's first experiences with a system can then affect their trust in the system in the future so it will be necessary that MASS are tested sufficiently before they are given to operators (Yu et al., 2019).

### **5.3.2.1 Supporting the operator's supervisory role**

One key requirement for ensuring that operators can trust MASS systems is that they can sufficiently supervise and maintain an oversight of the automated systems, to be able to fulfil their role as a supervisor. This has also been found when investigating seafarers' trust in future onboard automated systems (Chan et al., 2023). Figure 5.3 shows different design and training principles for MASS operations, that could be used to ensure that the operator has the ability to maintain an oversight of the MASS. This oversight could be achieved through factors such as how the information is displayed and the operator's training and experience levels. To be able to monitor the MASS effectively, it will be important to consider the design of the operator's display indications and ensure that information such as system mode and the status of safety-critical systems (e.g., communication links) are clearly displayed. To aid the development of appropriate trust in the information being reported to the operator via the system, participants discussed how it will be necessary for the operator to have an indication of how current the information being displayed. It has been highlighted that there is the potential for communications to be delayed or lost between a MASS and its RCC; therefore, an indication of how current the information is would allow the operator to rely on it appropriately (Ringbom, 2019; Thieme et al., 2018).

Another recommendation that was suggested to promote operators forming calibrated trust was providing system updates on what the system is doing and why during an operation, to allow operators to evaluate the system's decisions. It has been found that using higher levels of system transparency, such as including system reasoning and ratings of uncertainty in the information, can increase the operator's trust levels in the operation of uncrewed vehicles and highly automated vehicles (Li et al., 2023; Mercado et al., 2016; Sadler et al., 2016). However, it has been suggested that MASS operators might not trust collision avoidance systems that perform manoeuvres differently from how they would have, suggesting that the operator's strategies could also affect trust in addition to understanding the system's decision-making (van de Merwe et al., 2022a). If

operators are sceptical of such systems they may over-sample information and potentially increase their workload as they will put in more mental effort (Moray, 2003).

For operators to be supported in their ability to monitor the systems they will require experience with the MASS performing its tasks in an operational context, to develop an understanding of the system's behaviour. This experience will also be required as it can take time for an automated system user to develop stable trust in a system, and the amount of time may depend on the complexity of the system (Hancock et al., 2011; Hoff and Bashir, 2015; Lingg and Demiris, 2023; Parnell et al., 2022; Yu et al., 2019). Barrett-Pink et al. (2019) found that Royal Navy operators lacked trust in some of their current automated systems due to them not working in the way the operators anticipated. This suggests that it will be important that the operators receive sufficient training on the systems before they are deployed, so they are aware of the systems expected behaviour (Barrett-Pink et al., 2019; Koustanaï et al., 2012; Krampell et al., 2020).

### **5.3.2.2 Supporting the operator in processing the digital information**

Another factor that was found to be important to the MASS operators' trust was their ability to process digital information due to their lack of physical cues during remote operations. Figure 5.4 shows the principles for supporting operators in cross-referencing and validating digital information. It has been found that there are concerns that the operators may find it more difficult to maintain their SA as they will have to trust the digital information without being able to verify it through their senses; this has also been found when investigating the effects of future remote operations (Man et al., 2014; Palbar Misas et al., 2024; Wahlström et al., 2015). It has been suggested that trust and SA have a relationship in the context of monitoring MASS and, although the findings were not clear, it does suggest that SA should be considered as a factor in forming calibrated trust (Gregor et al., 2023). The operator will be heavily reliant on the navigation systems due to the lack of 'ship sense' and it has also been suggested that operators will need seagoing experience to ensure they have the navigational expertise, as well as additional experience and training with MASS to maintain their SA (Yoshida et al., 2020). Therefore, it will be important that operators receive training on how to correlate different pieces of digital information to validate the information and that systems are designed to take into account multiple sources so that operators can trust the information they are receiving from the MASS (Palbar Misas et al., 2024).

### **5.3.2.3 Handling system faults and recovering the MASS**

The ability to diagnose and respond to system faults was found to be an important factor in MASS operators achieving calibrated trust; the design and training principles generated are shown in Figure 5.4. Similar to previous findings on trust in automation, it was found that system reliability can lead to reduced operator trust during the operation of automated systems (Chavaillez et al., 2016; Lee

and Moray, 1994; Manzey et al., 2012). Previous research has found that seafarers might not accept and trust automated systems as there is a chance that the system may fail - even if the probability of such a failure is low, suggesting it may be difficult for operators to trust MASS systems (Man et al., 2023). Similar findings have also been reported when investigating uncrewed maritime systems, as system performance-related factors such as system reliability and system failure rates were found to be the most important to their trust when making decisions during an uncrewed maritime system game (de Rosa and Strode, 2022). Therefore, it will be necessary to ensure operators are aware of the types of faults that may occur, and the likelihood and consequences of various system faults to form accurate expectations of the system's reliability.

However, it has been shown that operators of automated systems can have difficulties in accurately calibrating their trust levels with the actual reliability of a system (Chavaillaz et al., 2016). In this study, participants suggested that indications of the error in the sensor data and the accuracy of the principles from an automated system could promote calibrated trust. After a system failure operators may need time to rebuild trust in the MASS (Dzindolet et al., 2002; Lacson et al., 2005). The amount of time to rebuild their trust could partially depend on the operator as it has been shown that individual differences can affect the impact an automation error has on operator trust (Pop et al., 2014). Explanations of why the failure occurred could repair trust in a HMT given the systems are using higher levels of automation, so operators could receive notifications or feedback from the system to explain the fault (de Visser et al., 2018).

Due to the operator mainly supervising the MASS at higher levels of automation, complacency was discussed as a concern as operators could become over-reliant on the automated systems (Bailey and Scerbo, 2007; Dreyer and Oltedal, 2019; Hogg and Ghosh, 2016; Parasuraman and Riley, 1997). Complacency has been seen in navigation officers of conventional ships, where the officers' failure detection of an autopilot system was low and the officers showed a lack of SA (Pazouki et al., 2018). Chan et al. (2020) investigated navigation officers' performance when supervising a radar display and the finding showed similar behaviour when 70% of the officers failed to detect gyro drift whilst monitoring the radar displays. Palbar Misas et al. (2024) found that even though most of the navigational students only slightly trusted their systems, it still took the participants eight minutes on average to stop trusting a faulty system. This suggests that there may be other factors that influence reliance and complacency. However, it will be important that operators are not only aware of potential system faults or cyber-attacks occurring but they also have experience with the types of occurrences so they can apply this awareness in real-world scenarios (Palbar Misas et al., 2024). Training for abnormal operations has been used to prepare operators for system failures by giving them more realistic expectations of the system and reducing the likelihood of them over-trusting the automation, which could help operators recognise system faults (Bahner et al., 2008; Manzey et al.,

2006). It has been found that receiving training on automated maritime systems and using alarms would increase seafarers' levels of trust and SA (Chan et al., 2023).

### 5.3.3 General Discussion

This chapter investigated the factors that influence a MASS operator's trust using the SAW taxonomy to analyse the participants' responses to the T-SWARM prompts about their experiences of MASS operations and the four key areas identified from the SWARM interview analysis in Chapter 4. The findings show multiple factors influence trust within HMTs, which will need to be considered both in the design of future MASS systems and the training of operators to support the formation of calibrated trust (Hoff and Bashir, 2015; Kaplan et al., 2023; Schaefer et al., 2016).

The findings highlighted the need to give operators the opportunity to develop appropriate mental models and, therefore, expectations of a range of operational scenarios (Hancock et al., 2011; Yoshida et al., 2020). In addition, operators will require time and experience to rebuild trust after a system failure (de Visser et al., 2018). Operators will require knowledge of the types of failures and training on how to handle those failures, including when or when not to take manual control (Bahner et al., 2008; Chan et al., 2023; Manzey et al., 2006). To effectively monitor the automated systems, operators will need to be provided with multiple sources of information and training on verifying digital information (Palbar Misas et al., 2024).

SWARM has previously been used to generate user-centred design recommendations for a future flight deck engine monitoring tool that could be used to aid their decision-making in a bird strike scenario by using pilots' interview responses to develop the recommendations (Parnell et al., 2021b). It has been suggested that engaging users in the design process of future systems will be important in the development of future maritime systems (Vu and Lützhöft, 2020a). It has also been applied to generate design recommendations for flight deck instrumentation to support operators in dealing with an engine oil leak by exploring how a pilot's response could be supported by the use of an engine monitoring assistant system (Banks et al., 2021). This demonstrates how SWARM can be applied to hypothetical scenarios to aid in the development of future systems. The design and training principles generated here have similarities with the recommendations generated by Parnell et al. (2022) to support UAV operator trust. For example, the need for operators to have time and experience working with the system and the ability to understand and manage failures in the system (Parnell et al., 2022), showing the utility of applying SWARM to generate operator focused design principles specifically for trust in uncrewed vehicle operations.

One limitation of the study was due to the difficulties in eliciting schema data, as discussed in Chapter 4, as mental models are not always as easily consciously recalled as other elements of perceptual cycle data, such as world information. This could explain why there were far fewer

schema references versus action and world references (Plant and Stanton, 2013a; Plant and Stanton, 2015). Another limitation of the study was that a small sample size was used for the interviews; due to the infancy of MASS, there is currently a limited number of operators and subject matter experts with relevant experience. Some of the participants did not have direct experience operating MASS, so further work will need to consider MASS operators' trust in real-world or realistic simulated scenarios to validate the generated principles. However, the findings do provide an initial understanding of factors that influence trust amongst MASS operators and subject matter experts with relevant knowledge and experience. Future research should further investigate MASS operators' trust using a larger sample size. This study extended the application of the aviation method SWARM to another safety-critical domain and the operation of other uncrewed vehicles. Future research should explore the application of T-SWARM to HMTs in other domains and the effects of uncrewed operations on trust.

## 5.4 Conclusion

This chapter has explored uncrewed MASS operators' trust using the semi-structured interview method T-SWARM to develop design and training principles to support operators in forming calibrated trust with MASS systems. The results showed there are challenges in supporting operators' trust due to the remote nature of uncrewed MASS operations and the lack of physical cues for the operators to reference. Additionally, operators will need support in relying on the systems appropriately as they will be supervising highly automated systems. The principles developed were in four key areas: ensuring operators develop appropriate expectations of the automation, are supported in their role of overseeing the systems, that operators are supported in the processing of different sources of digital information to verify its accuracy and aid them in diagnosing and responding to any system faults. The theoretical framework of the PCM was used to show how an operator's trust is experienced, informed by world information and acted upon during MASS operations. Future research should explore the validation of these findings in real-world scenarios and investigate the dynamics of operators' trust over time.

The findings of this chapter show the need to consider trust when designing future MASS systems due to its high level of influence on decision-making in HMTs and further demonstrate the connections between trust, transparency and decision support systems. It has also shown how an operator's mental models may impact trust and how their experience of crewed operations and lack of experience operating uncrewed may reduce their trust. The next chapter will focus on another factor within the decision-making factors in HMT model, the tasks and roles allocated to the operator during the operation of MASS, to investigate the types of error that could occur in the system. The

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approach will be used to investigate the operator's tasks in more detail and to suggest remedial strategies for HMIs at RCCs to mitigate the likelihood of design-induced errors.

# Chapter 6 Predicting design-induced errors in a Maritime Autonomous Surface Ship Remote Control Centre

## 6.1 Introduction

This chapter aims to understand what errors might occur in the operation of MASS from an RCC for an environmental survey by investigating the task-specific interactions within the HMT. In the decision-making factors in HMT model, two of the key decision-making factors were task/role allocation and decision support systems. In this chapter, these two factors will be investigated to explore what mitigation strategies could be used to reduce the likelihood of design-induced errors occurring when operating a MASS from an RCC using an HMI. This approach is being applied at the early stages of a systems design, to first understand what tasks the operator would be performing during a survey in both normal and abnormal operations before the system is fully developed. The normal and abnormal operational tasks are being compared to show the role of the MASS operator when using a highly automated system. After the operator's tasks have been identified, the tasks will be analysed to predict the types of errors that might occur. The previous chapters of the thesis have investigated decision-making at a higher level, whereas this chapter will focus on the sharp end of MASS operations by considering the specific types of interactions between the operator and their HMI.

### 6.1.1 Error in the maritime domain

MASS will be operated differently from conventional vessels, as the operators will no longer be on board; the operators at the RCC will still be an important part of the MASS system (Cao et al., 2023; Liu et al., 2022b). Operators at RCCs will still be responsible for maintaining oversight of the vessels' technical systems, overseeing the automated navigation systems and making decisions that the vessels' automated systems are unable to handle, as discussed previously in Chapters 4 and 5 (Dybvik et al., 2020; Hoem et al., 2018; Ramos et al., 2019; Størkersen, 2021). The design of the systems at the RCC will be important in ensuring that operators are appropriately supported in their monitoring tasks and taking back control from the automated systems that are no longer able to handle a situation (Dybvik et al., 2020; Mallam et al., 2020). It will be important to investigate what errors might occur whilst an operator is carrying out their tasks at the RCC and how the systems at the RCC can be designed to support the operator and minimise the risks associated with MASS operation.

'Human error' is often stated as the cause of maritime accidents; however, it is important to consider MASS as a complex sociotechnical system and understand that incidents and accidents are a result of systemic errors due to the design of systems rather than focusing on the individual operator (Read et al., 2021; Wróbel, 2021). In addition to the similar risks associated with conventional vessels, MASS have the potential to introduce other modes of failure due to their different way of operating (Ahvenjärvi, 2016; Hoem, 2020). For example, the situation where the MASS loses its connection to the RCC and the operator is no longer able to monitor the MASS or take back control when necessary (Burmeister et al., 2014b; Kim and Schröder-Hinrichs, 2021; Ventikos et al., 2020). Conventional maritime accidents have been investigated to explore what might have occurred if the ships had been uncrewed, and it was found that it was expected that it may have reduced the occurrence of navigational accidents, but non-navigational accidents (e.g., fire and structural failures) may increase (Wróbel et al., 2017).

Zhang et al. (2020) investigated the potential errors and their probability in emergency responses for an uncrewed cargo MASS, and it was found that the potential for errors was higher for the operation of MASS versus a conventional vessel. The errors involved in the operation of MASS in collision avoidance scenarios have been investigated, and takeover failures were identified as a key error and having adequate time to recover their SA would be a key factor (Cheng et al., 2024b). Also, when considering the potential errors in collision avoidance scenarios, it has been highlighted that the operator will require an adequate HMI that reduces the likelihood of selecting the wrong buttons or performing actions on the wrong objects (Ramos et al., 2019). Operational errors have been predicted for MASS HMIs, showing tasks such as setting a target route, setting the system configurations, and performing collision avoidance from shore have high probabilities of operational errors and demonstrated the importance of the HMI design (Liu et al., 2022b).

Human Error Identification (HEI) methods can be used to identify and predict the impact of errors in HMTs (Kirwan, 1998; Stanton and Stevenage, 1998). HEI methods are predictive and, therefore, useful in the early design stages of a system to suggest changes to mitigate potential errors before a design is further developed. To identify the types of errors that could occur within the HMT, Hierarchical Task Analysis (HTA; Annett et al., 1971) and Systematic Human Error Reduction and Prediction Approach (SHERPA; Embrey, 1986) will both be applied, SHERPA was selected as the HEI method as it has a high predictive validity (Baber and Stanton, 1996). HTA will first be used to describe the tasks involved in operating a MASS for an environmental survey. Next, SHERPA will be used to analyse what errors may occur at each stage of the operation and assess the likelihood and consequences of those errors. The results of the error analysis will be used to suggest design-focused mitigation strategies that might reduce these potential risks.

### **6.1.2 Hierarchical Task Analysis and Systematic Human Error Reduction and Prediction Approach**

HTA is a method used to decompose a system goal into sub-goals that need to be performed to complete the system goal. These tasks are then broken down further into subtasks to show all the different subtasks required to complete that specific task (Stanton, 2006). These sub-goals are then organised into plans to show the order in which the subtasks need to be performed to complete that task (Stanton, 2006). A hierarchy of the tasks involved in achieving the overall goal is created, which describes the work that is taking place (Stanton, 2006). The HTA can then be used to investigate sources of error that might occur whilst those tasks are being performed (Stanton, 2006). HTA has been selected as the technique to perform the task analysis as it is a flexible method which has been used across various domains, and it can be used to analyse tasks to any required level of detail depending on the purpose of the analysis (Stanton et al., 2013). The developed HTA can then be used as an input for other methods, such as error prediction in this case (Stanton et al., 2013).

HTA has been previously applied in the maritime domain to describe an operator's tasks during a MASS' collision avoidance with a crewed ship, to investigate what human failure events may occur during collision avoidance scenarios (Ramos et al., 2019), to investigate errors in pilotage operations (Ernstsen and Nazir, 2018) and to provide a basis for the design of software to support SA (Schaathun et al., 2013).

SHERPA is a human factors method used for predicting errors during a set of tasks or an operation (Embrey, 1986). SHERPA has been applied in a wide range of domains, such as aviation, predicting flight deck designed induced errors (Harris et al., 2005) and to investigate and mitigate failures caused by an engine bird strike scenario (Banks et al., 2022), in health care to predict administrative errors (Lane et al., 2006) and errors in prescribing specialist medications (Chana et al., 2017), in road to evaluate in-vehicle interfaces (Harvey and Stanton, 2012) and in maritime to predict errors during pilotage in constrained waters (Ernstsen and Nazir, 2018).

## **6.2 Method**

### **6.2.1 Hierarchical Task Analysis for an environmental survey development**

Similar to Chapter 4 an environmental survey was used as the use case for the development of the HTA as this will be a common use for MASS (Barrera et al., 2021; Devaraju et al., 2018). The HTA was conducted by following these steps (Stanton, 2006):

1. The first stage of creating the HTA was to define the boundaries of the system description for the HTA.

2. Next the overall system goal (goal 0) was defined.
3. The overall goal was then broken into main goals (e.g., goals 1, 2 and 3) that are required to meet overall goal, and these were then further broken down into sub-goals (e.g., goals 1.1, 1.2 and 1.3)
4. Each sub-goal was then broken down further into operations (e.g., 1.1.1 and 1.1.1.1) and continue to break down these operations until the task analysis is fit for purpose
5. The next stage of generating the HTA was linking the goals to the sub-goals by creating plans, to describe the order in which the sub-goals are performed and under what conditions they might be triggered (Stanton et al., 2013). The different types of HTA plans are shown in Table 6.1 and will be used to describe the order in which the tasks are completed.
6. The analysis was then reviewed by SMEs and refined.

Table 6.1 - Example HTA plans, showing the different types of plans (Source: Stanton et al. 2013).

Plan	Example
Linear	Do 1, then 2, then 3.
Non-linear	Do 1, 2 and 3 in any order.
Simultaneous	Do 1, then 2 and 3 at the same time.
Branching	Do 1; if X present, then do 2 then 3, but if X is not present, then EXIT.
Cyclical	Do 1, then 2, then 3 and repeat until X.
Selection	Do 1, then 2 or 3.

The overall goal (goal 0) in this case was defined as completing an environmental survey of a given area. The following boundaries were used to define the tasks under analysis, the MASS was being operated uncrewed and beyond the line of sight of the RCC, the MASS route and activities had been pre-programmed into the system, the system was capable of automated navigation and collision avoidance and the MASS start procedures had been carried out and it had been launched. To create the hypothetical HTA various sources were used as the system was still under development and not currently in use for any operations. These sources were training materials that have been developed for the future operators of the system that described how they will be able to carry out their tasks via their HMI. The training materials included a breakdown of the different components of the HMI, the steps they would need to go through when executing an environmental survey and the response to some of the key alerts they might experience during an operation. Software testing of the new system was also observed to understand how the operators would be interacting with the HMI

during different scenarios, showing the tasks being performed. System design documentation was used to understand the types of system alerts and faults that might occur during an operation and how an operator would be expected to respond to these types of alerts. These three sources were used to develop an initial HTA, which was then reviewed in a three-stage process by three SMEs to validate the HTA, as they had extensive knowledge of how the operator would be operating the system. One of the SMEs was involved in training the future operators, and the other two SMEs had been involved in the design of the HMI and MASS systems. All three SMEs had experience operating the prototype MASS during trials, so they were able to fill in any missing tasks and make any corrections to the HTA. After the HTA was created the HTA operations were all assessed for whether they would be performed during a normal operational scenario or abnormal operations.

### **6.2.2 Systematic Human Error Reduction and Prediction Approach**

SHERPA was used to investigate the potential errors that might occur when MASS are operated uncrewed for an environmental survey. To conduct SHERPA eight main steps were carried out (Stanton et al., 2013):

1. Conducting the HTA (see section 6.2.1 for further details).
2. Next each task from the HTA was classified using the SHERPA behaviour taxonomy. The five behaviour taxonomies are: Action, Retrieval, Checking, Selection, and Information communication (shown in Table 6.2).
3. The next stage of the analysis considered the error mode associated for each behaviour identified in the previous step, to judge which error modes could be possible. The SHERPA error taxonomy is shown in Table 6.2.
4. Once the potential errors were identified for each task, the consequences of these errors were then assessed.
5. Next the possibility of the if the errors being recovered in a later task step in the HTA was assessed.
6. After that the likelihood of the error occurring is rated here as either low (L), medium (M) or high (H) likelihood, these ratings were based on system documentation developed by SMEs. High likelihood was defined as errors that could be foreseen occurring on a regular basis during an operation, medium likelihood errors were those that might not occur regularly in operations but might occur in a few or multiple operations, and low likelihood were errors that could occur but would be unlikely to be seen over multiple operations but could feasibly occur.
7. Once the likelihood of the error occurring is determined the next stage is to assess the criticality of the error occurring, these ratings were also based on system documentation developed by SMEs. High criticality was defined as errors that meant the MASS was any errors that impacted the safety of the MASS, medium criticality was errors that impacted the MASS' ability to conduct

survey tasks and low criticality was defined as any other minor errors that did not impact safety or operational capability.

8. The final stage was to propose remedial strategies for the key errors.

Table 6.2 - SHERPA error modes and their description (Stanton, 2006).

<b>Error mode</b>	<b>Error description</b>
<i>Action</i>	
A1	Operation too long/short
A2	Operation mistimed
A3	Operation in wrong direction
A4	Operation too much/little
A5	Misalign
A6	Right operation wrong object
A7	Wrong operation right object
A8	Operation omitted
A9	Operation incomplete
A10	Wrong operation on wrong object
<i>Information retrieval</i>	
R1	Information not obtained
R2	Wrong information obtained
R3	Information retrieval incomplete
<i>Checking</i>	
C1	Check omitted
C2	Check incomplete
C3	Right check on wrong object
C4	Wrong check on right object
C5	Check mistimed
C6	Wrong check on wrong object
<i>Information Communication</i>	
I1	Information not communicated
I2	Wrong information communicated
I3	Information communication incomplete
<i>Selection</i>	
S1	Selection omitted
S2	Wrong selection made

## 6.3 Results

### 6.3.1 Hierarchical Task Analysis

An extract of the HTA of the operator’s tasks during the operation of an uncrewed MASS for an environmental survey is shown in Figure 6.1, the full HTA is included in Appendix E including the plans that describe the order in which the tasks should be performed. The HTA was found to have three main goals, 23 sub-goals and 421 operations and Table 6.3 shows the breakdown of the sub-goals and operations for each main goal. The three main goals were to execute the survey steps (main goal 1), oversee the MASS’ navigation (main goal 2) and monitor the MASS system alerts (main goal 3). The HTA showed that these three tasks will need to be performed simultaneously as the operator is responsible for having oversight of the survey itself, the navigational safety of the MASS and the health of its systems during the entire survey operation.

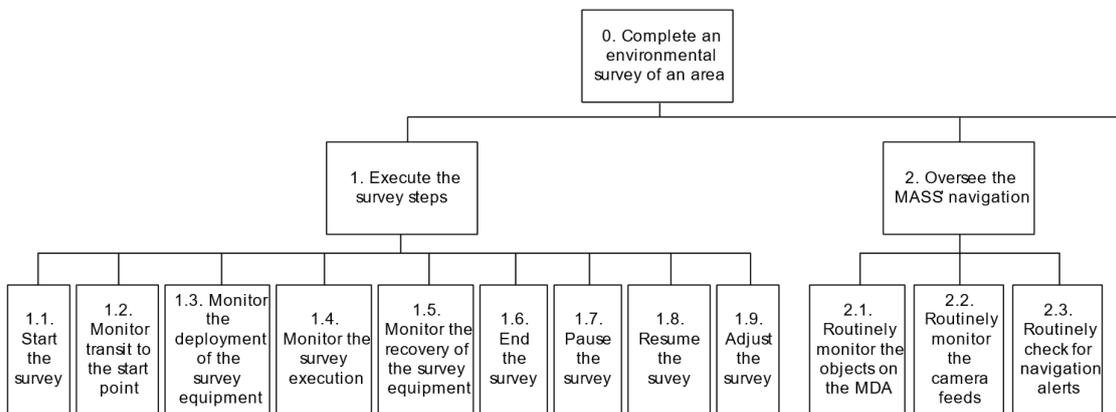


Figure 6.1 – Section of the HTA showing the overall goal, main goals and sub-goals.

Table 6.3 - The number of sub-tasks and operations for the three main tasks in the HTA.

Main Goal	No. of Sub-Goals	No. of Operations	No. of Normal Operations	No. of Abnormal operations
Execute the survey steps	9	193	44	149
Oversee the MASS’ navigation	3	149	9	140
Monitor the MASS system alerts	11	79	2	77
Total	23	421	55	366

The sub-goals were then decomposed into operations, the number of which is shown in Table 6.3. The operations were then assessed based on whether they would be performed in a normal

environmental survey operating scenario, e.g., a scenario where an operator did not need to respond to an alert or any system fault and was just carrying out the survey as planned, or abnormal where that operation would only be performed in an unanticipated scenario. Table 6.3 shows that only 15% of these tasks would be carried out during a normal operation if the survey went as intended. This showed that the operator will have minimal interaction with the MASS only to start, pause, stop and adjust the survey route for coverage as they will otherwise be monitoring the MASS should only need to interact with the MASS in response to any navigational or system alerts. 71% of the normal operations were found to be checking tasks showing that the majority of the operator's work would be supervisory.

### 6.3.2 Systematic Human Error Reduction and Prediction Approach

The next stage of the analysis was to consider what errors could occur when performing each operation. A total of 510 errors were identified using SHERPA, there were a total of 323 action failures, 89 checking failures, 60 selection failures, 29 information communication failures and 9 information retrieval failures. Table 6.4 shows the frequency of each failure identified for each of the failure categories and sub-categories. The majority of the failures were in the action category which has 63% of the total failures. The second most common failure category was checking errors (17% of the total errors), followed by selection errors (12% of the total errors). The highest sub-category was within the action category, the majority of the errors were if the operator omitted an action (33% of the total errors) for example, failing to take manual control or adjust the speed or heading of the MASS. The second highest sub-category was also an action sub-category, performing the right operation on the wrong object (17% of the total errors) such as, adjusting the speed rather than the heading or deleting the wrong survey observation or turning on the wrong back up sensor. The third highest sub-category was check omitted in the checking category (15% of the total errors), if the operator failed to check the status of different systems, navigational hazards and system faults on the HMI. 71% of the tasks for normal operations were classified as checking tasks, followed by 27% were action tasks and 2% were selection tasks, which shows that the majority of the operator's tasks are monitoring rather than interaction tasks with the system.

Table 6.4 - Frequency of failure for each failure sub-category

Failure Categories	Failure sub-categories	Failures Frequency (n)
Action	Operation too long/short (A1)	0
	Operation mistimed (A2)	0
	Operation in wrong direction (A3)	0

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	Operation too much/little (A4)	2
	Misalign (A5)	0
	Right operation wrong object (A6)	89
	Wrong operation right object (A7)	63
	Operation omitted (A8)	166
	Operation incomplete (A9)	2
	Wrong operation on wrong object (A10)	1
	Total	323
Information Retrieval	Information not obtained (R1)	8
	Wrong information obtained (R2)	1
	Information retrieval incomplete (R3)	0
	Total	9
Checking	Check omitted (C1)	76
	Check incomplete (C2)	12
	Right check on wrong object (C3)	0
	Wrong check on right object (C4)	0
	Check mistimed (C5)	1
	Wrong check on wrong object (C6)	0
	Total	89
Information Communication	Information not communicated (I1)	18
	Wrong information communicated (I2)	7
	Information communication incomplete (I3)	4
	Total	29
Selection	Selection omitted (S1)	27
	Wrong selection made (S2)	33
	Total	60
Total failures		510

The results of the likelihood and criticality of each of these errors are shown in Table 6.5. The most common error rating was the low likelihood and medium criticality category (275 errors), 54% of the errors were in this category. The second most common likelihood and criticality rating category was low likelihood and low criticality which was 25% of the total errors (130 errors). However, the low likelihood and criticality errors will not be analysed further, as the analysis will focus on the errors which are more likely to occur and are more critical. The majority of the errors were found to have a low likelihood as 94% of total errors had a low likelihood with carrying degrees of criticality. Table 6.6 shows examples of the key failure types in each likelihood and criticality category.

Table 6.5 - The frequency of failure likelihood and criticality ratings

	Likelihood		
Criticality	Low	Medium	High
Low	130	8	0
Medium	274	21	0
High	73	4	0

After identifying the key error types and assessing their criticality and likelihood the next stage of the analysis was to consider remedial measures for these errors to mitigate the risks. Table 6.7 shows the list of the 46 key errors found by carrying out SHERPA and the suggested design-based remedies that could be applied to HMIs, to reduce the possibility that these errors could happen whilst operating MASS. The key errors were selected from the higher likelihood and criticality rating categories, only the low likelihood and low criticality errors were excluded, and the errors were grouped where similar errors were found in different tasks. Remedial measures were then proposed that focused on how the HMI could be re-designed to reduce the error potential in these tasks. Many of the key errors involved failing to perform a check particularly in response to an alert, remedial strategies such as increasing the saliency of the alerts and prompting operators to make those relevant checks in response were suggested to aid the operator. Other key errors involved performing an action, e.g., failing to resume manual control, putting the survey equipment in the correct operation mode or adjusting the speed/heading incorrectly, which showed the need to consider the design of the HMI inputs to reduce the chances of errors being made and escalation of warnings for resuming manual control.

Table 6.6 - Examples of key failures identified within the SHERPA as categorised by likelihood and criticality.

	Likelihood		
Criticality	Low	Medium	High
Low	N/A	<ul style="list-style-type: none"> <li>• Fails to check the MASS parameters versus the survey activity and its progress for each survey activity</li> <li>• Fails to monitor the MASS' transit to the recovery and end points</li> <li>• Fails to check any added activities to the survey plan</li> </ul>	0
Medium	<ul style="list-style-type: none"> <li>• Fails to monitor the MASS position and speed when transiting to the start and end points</li> <li>• Failing to take manual control and perform the rest of the survey activities manually</li> <li>• Fails to abort the survey when there is an issue with the MASS system</li> <li>• Fails to check the MASS health status for minor faults and/or check the full fault list</li> <li>• Adjusting the speed/heading in the wrong direction to reach the waypoints</li> <li>• Fails to activate the correct sound for the collision avoidance manoeuvre</li> </ul>	<ul style="list-style-type: none"> <li>• Adjusting the speed incorrectly for survey equipment deployment or collecting the data</li> <li>• Adjusting the speed or heading of the MASS incorrectly in response to a sensor fault</li> <li>• Failing to check for system faults and for the specific details of the fault</li> <li>• Failing to check the speed through water when notified that the MASS is responding poorly to the speed command</li> <li>• Failing to check the alert table for multiple faults</li> </ul>	0

	<ul style="list-style-type: none"> <li>• Fails to make the supervisor or maintainer aware of a system fault/fails to provide them with all the information about that fault</li> <li>• Fails to communicate with the support vessel team/gives the support vessel team incorrect information</li> </ul>		
High	<ul style="list-style-type: none"> <li>• Fails to check the CPA and TCPA for objects on the MDA and tracks in the track table</li> <li>• Failing to monitor the camera feeds for hazards</li> <li>• Failure to check for navigational alerts</li> <li>• Fails to check the speed sensor warnings and that the speed sensor is available</li> <li>• Fails to check the MASS health status for major faults and/or check the full fault list</li> <li>• Fails to check the MASS stops in response to a steering fault</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to check the MASS health status in response to warning about speed and heading commands not being followed by the system or an automation inhibited alert</li> <li>• Fails to check water depth on a chart when the depth sensor fails</li> <li>• Fails to check the fault list for navigation system faults or fails to check the full list</li> </ul>	0

Table 6.7 - List of the key errors identified in the SHERPA and design-based remedies that could be applied to MASS HMI.

Error Failure	Remedial Measure
1. Fails to check the MASS health status in response to warning about speed and heading commands not being followed by the system	Increase the saliency of the alerts. Give prompts to check health of systems when alerts are given that speed and heading commands are not being followed
2. Fails to check water depth on a chart when the depth sensor fails	Include prompts for operator to check external sources when the depth sensor fails and ensure they have access to other sources of information
3. Fails to check the fault list for navigation system faults or fails to check the full list	Increase the saliency of the alerts. Give prompts to check health of systems when alerts are given that the automation is not behaving as expected or is inhibited. Prioritise the most critical faults at the top of the fault list and group the faults by system type where possible.
4. Adjust the speed value instead of the heading or vice versa	Ensure that there is adequate separation between the two inputs and that they are clearly labelled.
5. Adjusting the speed/heading the wrong way	Ask operator to confirm heading and speed inputs before they are sent to the MASS
6. Failing to resume manual control and make speed or heading adjustments to take collision avoidance action or engage the emergency stop if needed	Ensure that takeover request warnings are more salient and use an escalation of warnings as the collision risk increases
7. Fails to check CPA & TCPA for objects on the MDA and track table or fails to check for all the objects on the MDA or the full track table or fails to monitor these objects further	Regular prompts to check for collision risks and highlights objects that may pose a higher risk and an escalation of collision risk alerts.
8. Fails to check camera feeds for hazards or does not check all the camera feeds	Regular prompts to check all camera feeds
9. Failing to check that emergency systems (e.g., bilge pumps or fire suppression) have been activated and failing to manually activate them if not or activating the wrong system manually	Prompt to check emergency system is activated when first alerted to the emergency and another prompt to check that the incident is then resolved

10. Failing to navigate the MASS to a safe position with the remaining fuel and dropping the anchor	Display the distance that can be recovered with the remaining fuel and highlight areas with navigational hazards
11. Failure to resume manual control for a major system fault	Prompts after major system alerts asking operators do they need to resume manual control and include fault details to aid with this decision
12. Fails to ask the RCC supervisor for an appropriate course of action	Prompts to contact supervisor and decide a course of action
13. Fails to tell the supervisor of the environmental sensor warning	Prompts to contact supervisor and ask for an estimate of the environmental conditions
14. Operator receives an incorrect estimate of the environmental conditions from supervisor	Provide external environmental condition sources where possible to cross reference
15. Fails to check the speed sensor warnings and that the sensor is available	Increase the saliency of the alerts. Give prompts to the availability of the speed sensor.
16. Fails to check the water depth	Highlight water depth reading on HMI following water depth threshold alert
17. Fails to check alert banners or alerts table	Make alerts more salient, escalation of warnings
18. Fails to check MASS health status and/or fails to check the list for relevant faults	Ensure that the MASS health status is visible on the HMI at all times and provides a clear indication of the health status
19. Fails tell the supervisor and maintainer about a major system fault (e.g., steering fault) and further details of the fault or informs them about the wrong fault	Prompt operator to ask for assistance with navigational system fault
20. Fails to communicate with the support vessel or communicates incorrect information	Prompts to contact support vessel in the case of a system failure and highlight key information about the fault that may be needed
21. Fails to tell the supervisor about the fuel warning	Prompts to contact supervisor to tell them about fuel warning
22. Rebooting a different server to the survey equipment server	Ensure each server button is clearly labelled and there is adequate distance between the buttons

23. Fails to check the speed through water in response to a poor speed response	Prompt to check speed through water when there is a poor speed response alert
24. Turns off the power for a different piece of equipment	Clear indication of which pieces of equipment are powered on e.g., green icons and clear labels for each piece of equipment
25. Selecting the wrong back up sensor	Ensure that each backup sensor is clearly labelled and there is adequate space between each sensor button
26. Failing to turn the backup sensor on (depth sensor)	Prompt to check the backup sensor has been selected after the primary/secondary sensor has failed
27. Activating the wrong sound for the collision avoidance action	Ensure that the sound buttons are clearly labelled and there is adequate space between the buttons
28. Turns off a backup sensor that is already on	Clear indication of which backup sensors are powered on e.g., green icons and clear labels for each sensor
29. Fails to abort the survey	Clear indications each systems functioning and ability to obtain further details on faults
30. Fails to take manual control and deploy survey equipment manually	Ensure alerts are also relayed to the supervisor HMI
31. Fails to adjust speed during survey equipment deployment or recovery	Escalation of warnings and increase saliency of speed alerts for survey equipment deployment and recovery
32. Fails to put equipment in operational mode	Increase the saliency of the alert that the survey equipment is not in operational mode
33. Fails to turn off depth sounder	Prompt to turn off depth sounder when an acoustic interference warning is given
34. Failing to look closer at an object on the camera feed, moving the camera view and zooming	Prompt to check type of object when a new object is located
35. Failing to take manual control and carry out the rest of the survey steps in manual control	Ensure alerts are also relayed to the supervisor HMI
36. Fails to complete all the remaining survey activities	Give prompts and feedback on the next planned survey activities and notifications when activities are complete even in manual control

37. Fails to clear the e-stop and then restart the engines	Ensure the HMI has salient alerts that the e-stop has been engaged and a prompt that the engines will need to be restarted when the situation has been resolved
38. Fails to check the MASS progress and parameters for the survey tasks	Give notifications when survey activities are completed and provide the survey parameters in the activity summary
39. Fails to check position accuracy	Prompt to check position accuracy and indication on the HMI of when the position accuracy is higher than the set threshold
40. Fails to check tidal current and speed over ground information	Prompts to check tidal current information and speed over ground when speed through water information is unavailable
41. Fails to check the MASS position versus the survey region	Escalate warnings as MASS becomes closer to the edge of the survey region and show the predicted trajectory on the HMI to show the MASS will exit the survey region
42. Does not make the RCC supervisor aware of the positional accuracy issue	Ensure alerts are also relayed to the supervisor HMI
43. Fails to notify the supervisor of the AIS transmission fault	Prompts to contact supervisor to tell them about AIS transmission fault
44. Select the wrong observation from the list	Prompts operator to check and confirm it is the correct observation that needs to be deleted
45. Selects the wrong survey equipment mode or fails to select operational mode	Provide alerts when the survey equipment mode is not compatible with the survey activity before the activity is started
46. Fails to check an added activity	Prompt to check activity and confirm that all changes have been made when adjusting the survey plan dynamically

## 6.4 Discussion

Key potential errors in the operation of MASS for an environmental survey have been identified and remedial measures for MASS HMIs have been suggested to reduce the probability of the errors occurring in future operations (Table 6.7). The HTA was created by observing early-stage software testing and reviewing system documentation so that the task analysis could be carried out early in the design development before it has been finalised. SHERPA was conducted on all the HTA tasks including both the normal and emergency tasks, it has shown what remedial strategies can be applied to support both normal and emergency operations. As this application has shown the majority of the operator's tasks are related to handling emergency operations, this was also found in Chapter 4 by applying SWARM. Therefore, it will be important to ensure that the design of MASS HMI considers how operators will be alerted, or how they will interpret the information to identify an issue. Although the task analysis was carried out at an early stage in the design process, this error analysis provides insight into understanding the types of errors that may be seen when operating MASS using an HMI located at an RCC. Developing a detailed HTA at an early stage could then be used as a more detailed use case for further analysis such as predicting operators' workload and analysing the design of a future HMI (Stanton et al., 2013).

SHERPA has previously been applied in the maritime domain to explore the errors that could occur in pilotage (Ernstsen and Nazir, 2018), and air-maritime search and rescue (Hung and Dai, 2024). The findings here further demonstrate its utility in the maritime domain. It has also been applied to other safety-critical domains that utilise automation, such as aviation (Banks et al., 2022; Parnell et al., 2021a), showing its use in capturing the errors that can occur in human-machine interaction. The error analysis conducted here shows its use in considering the interactions when operating more highly automated systems. SHERPA has been shown to have high levels of reliability and validity, which make it a useful method when exploring novel technologies, where there are a limited number of experts (Stanton et al., 2002). Whilst SHERPA is not a systemic approach, it is a useful method to explore human-machine interaction. SHERPA shows how certain errors may appear to be the fault of an operator, but they might actually be induced by the system's design (Parnell et al., 2021a; Read et al., 2021). This analysis has shown there are still potential avenues for error in the operation of MASS, even though the automated system will conduct tasks such as route navigation and collision avoidance. Therefore, reducing the level of human input in these tasks does not make MASS inherently safer it just changes the types of error paths (Hoem et al., 2018; Mallam et al., 2020).

Although the majority of the errors in this case (94%) were rated as having low likelihood, it is still important to consider these errors as they could be essential for safety or critical for completing an accurate survey. Similar to Wróbel et al. (2017) findings that MASS would reduce the likelihood of navigational accidents but the consequences of some accidents, particularly non-navigational

accidents, were much greater. From the errors identified here, there were still errors rated as highly critical even though they had a low likelihood, further demonstrating that reducing human involvement to supervisory may not always increase safety.

The analysis showed that most of the errors were within the action category, where the operator omitted to act e.g., taking manual control or adjusting the MASS heading or speed. Cheng et al. (2024b) also found similar key errors in the analysis of errors involved in MASS collision avoidance tasks and a key performance-shaping factor was the operator's available decision-making time. This further demonstrates that remedial strategies such as increasing the saliency of those types of alerts making the request for the operator to intervene and escalating warnings to try and gain the operator's attention as early as possible. When operating highly automated MASS with automated collision avoidance systems like in the use case presented here, the backup response is still the operator performing collision avoidance as shown in the task analysis. Therefore, there is still a need to consider the HMI as a critical component, especially to aid in performing key tasks in the case of faults or abnormal operating scenarios (Liu et al., 2022b). The results of the error analysis extend Ramos et al. (2019) finding's relating to the requirements of an HMI to support collision avoidance tasks to include other tasks as well as collision avoidance and to consider the saliency of the alerts given and escalating the warnings if there is no intervention from the operator. Whilst collision avoidance tasks will be key to maintaining the safety of a MASS and the surrounding vessels, it is also important to consider other safety related tasks as responding to other hazards such as system failures is also an essential operator task.

Another key finding, in addition to the identified errors, was the types and number of tasks (15% of the tasks) conducted in normal operations versus abnormal operations and of those tasks that were considered normal operations 71% of the tasks were checking tasks where the operator is monitoring the automation. Insufficient vigilance and automation complacency have been found previously when investigating the potential errors in MASS operations (Hogg and Ghosh, 2016; Zhang et al., 2020), as identified here, many of the key errors are failures to check or perform actions rather than carrying out a task incorrectly. Due to the potential issues surrounding passive monitor behaviour when supervising automated systems operators, prompts may assist operators in performing checks when there are faults, and analysis also shows the importance of designing salient alerts.

Other errors were related to information communication and retrieval, where the operator might fail to tell the RCC supervisor that there is a particular fault or issue during a survey activity. Therefore, they might fail to ask for guidance on whether the survey should be continued or aborted. The results suggested mitigation strategies such as, including prompts for the operator to contact their supervisor or maintainer to ask for advice in these types of scenarios and additionally alerts need to

be relayed to the supervisor's HMI to reduce the chances of any alert being missed by both operator and supervisor. Communication between the members of the RCC team has previously been suggested as an essential skill for training future operators. Therefore, it will be necessary to consider how the system design can support communication with other human team members and the HMT interactions (Deling et al., 2020; Emad and Ghosh, 2023).

Other potential errors that may have been expected that have high consequences such as loss of communications with the MASS, which has been highlighted as key safety risk (Pietrzykowski et al., 2019; Tabish and Chaur-Luh, 2024; Wróbel et al., 2017), was not found to in the analysis. These types of errors were not found due to the design of the systems which trigger safe modes when the communication is lost, e.g., the MASS will hold position or return to a predefined safe zone or rendezvous point where it can be recovered to mitigate risks of collisions or groundings. However, SHERPA is limited to only considering the risks associated from the perspective of the operator's interactions with the system and in the case of a loss of communications with the MASS their ability to take action is limited. Other systemic methods could be used to explore these risks at the meso and macro system levels.

Similar to the findings in Chapter 4 from the SWARM interviews, the SHERPA analysis has shown that there is a need to consider the saliency of the alerts used for different features, provide clear indications on each system's functioning and give the operator information to support them evaluating the system's behaviour. There are similarities in the design principles generated from the SWARM interviews and the remedial strategies suggested in this chapter. However, the remedial strategies generated are more specific to the operator's tasks and interactions with the HMI and RCC team members than the design principles. For example, some of the remedial strategies suggested were specific prompts required to aid operators in responding to more specific alerts or situations they may encounter during a survey. Other remedial strategies expanded on the SWARM design principles, as the application of SHERPA has shown which alerts may be the most critical and should be prioritised in terms of their saliency and providing prioritised lists of system faults. This demonstrates that using a mixed methods approach can be beneficial as SWARM generates design principles with a broader focus capturing a wider range of the interactions between the HMT and SHERPA provides more remedial measures that are detailed to specific tasks.

### **6.4.1 Further work and evaluation**

There are limitations of this methodology as the likelihood and criticality ratings are subjective, as system documentation created by SMEs was used to classify the errors. Further validation of the likelihood and criticality of the errors could be done as more MASS are deployed for real-world use. As the technology for MASS continues to develop, it will be necessary to reconsider this error

analysis, as the types of errors may have changed. New remedial strategies may be required to mitigate the possibility of new errors being introduced by design or operational changes. Future work could include getting experienced MASS operators involved in rating the likelihood and criticality of the errors to increase the validity of the findings. The findings here could be compared to the errors associated with conventional vessels to understand how the introduction of higher levels of automation would change the potential errors. A limitation of SHERPA is that the analysis does not consider the interaction between the errors that might occur and the potential knock-on effects of multiple errors occurring and how this could impact safety risks. Future work should consider analysing the interaction effects between the types of errors identified using methods such as NETworked Hazard Analysis and Risk Management system (NET-HARMS; Dallat et al., 2018), to identify further system risks.

Further work should investigate how these remedial measures could be implemented into a MASS HMI and test which design concepts result in increased performance and reduced errors. Another limitation of this chapter is that only the lower levels of the system were considered, so the mitigation strategies were focused on the operator and system interactions. This approach could be extended to applying SHERPA at the meso and macro system levels to explore errors induced by system design at the system higher levels, to ensure the other influences in the sociotechnical system are considered. However, a sociotechnical system's analysis is conducted in Chapter 8 to investigate the decision-makers at the macro system level.

## 6.5 Conclusion

In this chapter, a HTA was produced to describe the operator's tasks during the operation of a MASS conducting an environmental survey. The development of the HTA showed that the majority of the operator's tasks will occur if abnormal scenarios are encountered due to a system failure or the environmental conditions, further demonstrating the potential for operators to have a passive role as discussed in Chapters 4 and 5. SHERPA was then applied to the HTA developed to explore what errors might occur during the MASS operation and then to assess the likelihood and criticality of those errors, to identify which were key errors. It was found that a high percentage of the errors (94%) were rated as low likelihood, however, 14% of the total errors were rated as low likelihood but had a high criticality. Similarly, there were also errors found that had a medium likelihood of occurring and medium and high levels of criticality although these were much fewer. Examples of the key errors with higher levels of criticality were the operator failing to monitor their interface and camera feeds for hazards and failing to intervene in collision scenarios or when a system failure has occurred. This analysis then provided 46 remedial strategies that focused on the design of MASS HMIs to support the operator in their ability to carry out their key tasks at an RCC. It has shown that

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operators may need prompts to guide them when handling system alerts and failures but there is a need to carefully consider the saliency of the alerts based on their priority. This application of HTA and SHERPA has shown how error analysis can be conducted at the early stages of a system's design.

This approach has further investigated factors from the decision-making factors in HMT model. The findings have shown the importance of considering the transparency of the decision support system and how the system will support communication in the HMT by identifying the potential for design-induced errors. This chapter has focused on the specific tasks that will be performed during MASS operation and to build on this analysis the next chapter of this thesis will explore how to promote teamwork within the HMT. Chapter 7 will focus on the factor teams from the decision-making factors in HMT model and the other factors associated with teams from the model. This will be achieved by investigating the human and machine behavioural competencies that are required for human and machine teammates to be able to work effectively as an HMT.



# **Chapter 7    Developing human-machine teams**

## **competencies: a Behavioural Markers System for**

### **Maritime Autonomous Surface Ship Operations**

#### **7.1    Introduction**

Previously, work in this thesis has explored MASS operators' decision-making processes and the tasks that they will conduct at RCCs. Next, this chapter investigates the competencies needed for human and machine teammates working in an HMT. The decision-making factors in HMT model developed in Chapter 2, showed that teams, the ability of the human and machine teammates to collaborate with each other was a key factor in the model. In this chapter, a novel Behavioural Markers System (BMS) will be developed to show what behaviours are needed within an HMT to create a collaborative environment, so that the HMT teammates can make joint decisions. The BMS will consider both sides of the reciprocal interactions between the human and machine teammates within the HMT. The behaviours outlined in the BMS could then be considered in the design of future systems to enable system designs to include behaviours that could enhance teamwork and improve team performance. The BMS will also be used to support the development of future standards and key performance indicators for MASS operators.

##### **7.1.1    Non-technical skills in Human-Machine Teams**

As the development of the technology is increasing MASS systems are using higher levels of automation and the interaction between operators and the systems is becoming more teammate-like than tool-like (McNeese et al., 2018; Seeber et al., 2019). It is therefore necessary to consider how operators and MASS systems can work together effectively as an HMT (Dominguez-Péry and Vuddaraju, 2020; Liu et al., 2022a). When designing sociotechnical systems, there is a need to consider the social interactions that support teamwork within HMTs, in addition to the system's technical capabilities (Walliser et al., 2019). It has been highlighted that current human-to-human models and methods for understanding teamwork need further development to be appropriate for the application to HMTs (Roberts et al., 2022). This chapter aims to explore how human-to-human models can be extended for HMTs from the perspective of the human teammate and the machine teammate.

For machine agents to be teammates they will need to have various teamwork competencies, such as the ability to communicate, coordinate and adapt to optimise the HMT's interactions (Stowers et

al., 2021). To display these types of behaviours the use of explainable artificial intelligence has been suggested to improve teamwork competencies within HMTs (Stowers et al., 2021). Machine agents will need to communicate effectively, anticipate the needs of their human teammates and coordinate their tasks with human team members (McNeese et al., 2018). There is also a need to consider how machine teammates will display more human-like behaviour, as even when human teammates are communicating with a system effectively negative performance has been seen due to system failures and a lack of human-like behaviour (Demir et al., 2016; Tokadlı et al., 2021). Audio-voice communication is one mode of communication that has been found to improve operator performance and the operator's perception of teaming (Bogg et al., 2021).

The automated systems will be involved in the team's decision-making and will need to share their reasoning with the operator to work collaboratively (Chen et al., 2018). It has been suggested that the automated systems need to meet certain requirements, such as monitoring the operator's actions and performance and supporting two-way communication to be considered a teammate (Tokadlı and Dorneich, 2023). These requirements will be needed to support coordination within the HMT (Tokadlı and Dorneich, 2023). The HMT will need to create a shared mental model to facilitate the teammates sharing information and an understanding of how to provide each other support (Grimm et al., 2023). Therefore, the machine teammate will need to understand the human teammate's tasks and how those tasks integrate with their machine tasks (Andrews et al., 2023; Grimm et al., 2023). The operator's trust in the system may also affect their ability to work with a machine teammate, as it may affect their communication with their machine teammate (Barrett-Pink et al., 2019; de Rosa and Strode, 2022; Hogg and Ghosh, 2016).

As higher levels of automation are used in MASS the operator will predominantly be monitoring the system to evaluate its functioning and recognising when it is no longer within its operational limits (Ramos et al., 2019; van de Merwe et al., 2022b). Similarly, in human-human teams performance monitoring is required so that teammates can give each other feedback and recognise signs of overloading in their teammates (Salas et al., 2005). In addition to the operator monitoring the system's performance, the system could be designed to monitor the operator's performance as would occur within human-human teams, techniques such as action recognition and assessing whether an operator's actions are consistent have been suggested (Burian et al., 2023; Mehak et al., 2024). Another aspect of human-human teamwork is providing backup behaviours to other teammates during levels of high workload by redistributing tasks within the team (Salas et al., 2005). Machine teammates could also be designed to estimate operator workload so that the tasks can be reallocated within the HMT (Giolando and Adams, 2024; Heard and Adams, 2019).

As MASS are a technology with new concepts of operation, specific standards and competencies for MASS operators' training are under development for inclusion in the International Maritime

Organisation's MASS code and this research aims to contribute to the development of those standards (Kim, 2024). Currently, bridge officers receive non-technical skills training during their Bridge Resource Management training. However, it has been suggested that current training should focus more on team training rather than individual performance, which could be updated to include guidance on working in an HMT (Fjeld and Tvedt, 2020; Praetorius et al., 2020).

MASS operators will need to develop their non-technical skills (e.g., their communication and leadership skills), which can be defined as their cognitive, social and personal resource skills to complement their technical or taskwork skills to increase the performance and safety of the HMT (Dubrow et al., 2024; Emad and Ghosh, 2023; Flin et al., 2008). Teamwork is the "interdependent components of performance required to effectively coordinate the performance of multiple individuals", (Salas et al., 2008, p.541) explaining how the operator will work within the RCC team. Although, the system's design should be considered first and other mitigation strategies will need to be applied to ensure the overall safety of MASS systems; training in non-technical skills will only partly address this issue (Salmon et al., 2023; Young and Steel, 2017). These teamwork competencies will need to be extended to working with machine teammates, so that they can be considered when designing systems, to help support operators in displaying these teamwork behaviours.

BMSs are used to evaluate and train operators in safety-critical industries including maritime for training bridge officers (da Conceição et al., 2017; Saeed et al., 2017). A BMS consists of several behavioural categories (e.g., communication, adaptability) within these categories the behavioural markers are split into sub-categories (e.g., for communication, exchanging information and giving instructions). Behavioural markers are "observable, non-technical behaviours that contribute to superior or substandard performance within a work environment"(Klampfer, 2001, p. 10). The behavioural markers within the categories can then be used to assess operators during training and operations to see which positive or negative behaviours are observed. However, in this chapter, a novel BMS is being developed that could be used to consider not only human behaviour but also machine behaviour.

The BMS developed for HMTs will consist of three groups of behavioural markers, the first group for human operators working with human teammates, the second group for human operators working with machine teammates and a third group for machine teammates working with human operators. For the machine teammates group these markers can be used in the design and evaluation of future systems, to support the HMT performance. The BMS will be developed using existing human-human BMSs, adapting them to be relevant for MASS and extending them to include behaviours to assess HMTs. The chapter also aims to validate the BMS through observations of an RCC in a different context.

## 7.2 Method

### 7.2.1 Human-Machine Team Behavioural Markers System stages of development

The BMS for HMTs was developed using three key stages:

1. An initial BMS was created using evidence from BMSs designed to assess human teams in multiple domains (see section 7.2.1.1).
2. Next, the initial human BMS was reviewed to consider the relevance of each marker for the interaction between a human and their machine teammate (see section 7.2.1.2.).
3. The initial human BMS was then reviewed again to consider the relevance of each marker from the perspective of the machine teammate interacting with their human teammate (see section 7.2.1.3.).

#### 7.2.1.1 Stage 1- Human Team Behavioural Markers Systems Review

An initial set of behavioural markers for human teammates was developed using evidence from existing BMSs that have been developed in other domains including: maritime for the assessment of deck officers of conventional ships during training (da Conceição et al., 2017; O'Connor et al., 2002; O'Connor, 2011; Saeed et al., 2017), for merchant marine engineers crisis management training (Gatfield, 2005), and for vessel operators in the tanker industry (Oil Companies International Marine Forum, 2018), in aviation to assess helicopter pilots during training (Hamlet et al., 2023), for the training of aircraft pilots (O'Connor et al., 2002), to assess air traffic controllers control strategies (Kontogiannis and Malakis, 2013) and to assess military pilots in operational settings (Tsifetakis and Kontogiannis, 2019), in medicine to assess neurosurgeons during simulator training (Michinov et al., 2014) and for assessing and training scrub nurses in theatre (Mitchell et al., 2011), in petrochemical for assessing drill crews in training and operations (Crichton et al., 2017), in rail to explore which failures in non-technical skills in network controllers increased risks during operations (Naweed and Murphy, 2023) and in fire and rescue to assess the performance of incident commanders during simulated training and live operations (Butler et al., 2020).

The main behavioural categories shown in Table 7.1 were developed from behavioural categories in the BMSs outlined above. Next, the relevant categories were renamed using some of the core components and mechanisms of teamwork outlined by Salas et al. (2005). The initial set of behavioural markers included eight behavioural categories, shown in Table 7.1. These were closed-loop communication, decision-making, leadership, performance monitoring, backup behaviours, adaptability, shared mental models and SA.

Table 7.1 – Behavioural categories and sub-behavioural categories identified from existing human-human BMS.

Behavioural Category	Behavioural Sub-category
Closed Loop Communication	Exchanging information
	Giving instructions
	Providing feedback to other human team members
Decision-making	Selecting and following regulations and procedures
	Identifying and selecting options
	Reviewing course of action
	Recognition Primed decision-making
Leadership	Setting and maintaining a team atmosphere
	Co-ordinating activities
Performance Monitoring	Monitoring the performance of other human team members
Backup behaviours	Recognising and providing assistance when a teammate is overloaded
Adaptability	Ability to adjust behaviour
Situational Awareness	Gathering information
	Comprehending informational elements
	Anticipating future states
Shared Mental Models	Understanding roles and responsibilities of self and human team members

### 7.2.1.2 Stage 2 – Human-Machine Behavioural Markers Development

Next, the human teammate behavioural categories were assessed for their relevance to the interactions between a human and their machine teammate, see Table 7.2. To determine if the behavioural marker was relevant to human-machine interactions, each behavioural marker was reviewed to see if the marker was:

- relevant to human-machine interaction without adjustment (i.e., it was already a behaviour that could be seen by a human interacting with a system),
- or relevant but needed adjustment (i.e., the behaviour could be seen in a human interacting with a system but the wording of the behavioural marker required changing to make sense for a machine teammate),

- or if it did not apply to a human interacting with a machine teammate, as the behaviour would only be relevant in a human-human team.

Table 7.2 – The behavioural categories and sub-categories that were found to be relevant for human-human teammate interactions, human-machine interactions and machine-human interactions.

<b>Behavioural Category</b>	<b>Behavioural Sub-category</b>	<b>Human-Human</b>	<b>Human-Machine</b>	<b>Machine-Human</b>
Closed Loop Communication	Exchanging information	✓	✓	✓
	Giving instructions	✓	✓	✓
	Providing feedback to other human team members	✓	✓	✓
Decision-making	Selecting and following regulations and procedures	✓	✓	✓
	Identifying and selecting options	✓	✓	✓
	Reviewing course of action	✓	✓	✓
	Recognition Primed decision-making	✓	✓	
Leadership	Setting and maintaining a team atmosphere	✓		
	Co-ordinating activities	✓	✓	
Performance Monitoring	Monitoring the performance of other human team members	✓	✓	✓
Backup behaviours	Recognising and providing assistance when a teammate is overloaded	✓	✓	✓
Adaptability	Ability to adjust behaviour	✓	✓	✓
Situational Awareness	Gathering information	✓	✓	✓
	Comprehending informational elements	✓	✓	✓
	Anticipating future states	✓	✓	✓
Shared Mental Models	Understanding roles and responsibilities of self and human team members	✓	✓	✓

	Understanding roles and limitations of machine team members		✓	✓
Trust	Demonstrating appropriate levels of trust	✓	✓	

The number of relevant, non-relevant and adjusted behavioural markers for each behavioural sub-category is shown in Table 7.3. The BMS was extended to include additional behavioural categories thought to be relevant to HMTs. These include trust and an additional sub-category within the shared mental models category. Trust is an important part of how an operator will interact with a machine teammate as discussed in Chapters 2 and 5, as it can affect their use and acceptance of a system. Although trust is a behaviour present in human-human teams, it was not found as a behavioural category in the human-human BMSs as it is not a behaviour commonly assessed for human-human teams. It has been included in Table 7.2 for completeness, as it is a behaviour in human-human teams but developing behavioural markers for human-human trust is beyond the scope of this work. The operator will need to create a shared mental model to understand the roles and limitations of their machine and human team members (Gisick et al., 2018). It will be important that the operator understands the division of work and roles in the HMT so that they can rely on and use the automation appropriately. The machine teammate will also need to have the ability to create a shared mental model so they can develop an understanding of what their teammate's tasks are and how the team is working together (Andrews et al., 2023; Grimm et al., 2023).

Table 7.3 – Behavioural markers development for human-machine interactions, the number of behavioural markers found to be relevant and not adjusted, relevant and needed to be adjusted, non-relevant, and additional markers for each sub-category of behaviours.

Behavioural Category	Behavioural Sub-category	No. of Human-Human BMs	No. of BMs relevant to Human-Machine and not adjusted	No. of BMs relevant to Human-Machine and adjusted	No. of BMs not relevant to Human-Machine	No. of BMs added
Closed Loop Communication	Exchanging information	10	1	3	6	0
	Giving instructions	4	1	2	0	0
	Providing feedback to other human team members	4	0	1	3	0
Decision-making	Selecting and following regulations and procedures	2	2	0	0	0
	Identifying and selecting options	7	7	0	0	0
	Reviewing course of action	3	2	1	0	0
	Recognition Primed decision-making	1	1	0	0	0

Leadership	Setting and maintaining a team atmosphere	7	0	0	7	0
	Co-ordinating activities	10	2	0	8	0
Performance Monitoring	Monitoring the performance of other human team members	3	0	1	2	0
Backup behaviours	Recognising and providing assistance when a teammate is overloaded	4	1	2	1	0
Adaptability	Ability to adjust behaviour	8	8	0	0	0
Situational Awareness	Gathering information	5	3	2	0	1
	Comprehending informational elements	4	3	1	0	0
	Anticipating future states	6	5	1	0	0
Shared Mental Models	Understanding roles and responsibilities of self and human team members	2	1	0	1	0
	Understanding roles and limitations of machine team members	0	0	0	0	2
Trust	Demonstrating appropriate levels of trust	0	0	0	0	6
Total		79	38	14	27	9

### 7.2.1.3 Stage 3 - Machine Behavioural Markers Development

The behavioural categories were then assessed again for their relevance to a machine teammate interacting with a human teammate and adjusted as needed to make them appropriate for a machine. Similar to the development of the human-machine behavioural markers, the behavioural markers were sorted into the three categories outlined below, was the behavioural marker:

- relevant to a machine interacting with a human without adjustment (i.e., it was already a behaviour that could be seen by a system interacting with an operator),
- or relevant but needed adjustment (i.e., the type of behaviour the marker described could be seen in a machine interacting with an operator, but the wording of the marker needed changing to make sense for a machine teammate)
- or if it did not apply to a machine interacting with a human teammate as the behaviour is not appropriate for a machine.

The number of relevant, not relevant and adjusted behavioural markers for each behavioural sub-categories are shown in Table 7.4. Another behavioural marker was added within exchanging information in the closed-loop communication category, to ensure that the machine teammate is sharing relevant information proactively and that this information is integrated in a way to make it more easily interpreted by the operator.

Table 7.4 - Behavioural markers development for machine-human interactions, The number of behavioural markers found to be relevant and not adjusted, relevant and needed to be adjusted, not relevant, and additional for machine-human interactions for each sub-category of behaviours.

Behavioural Category	Behavioural Sub-category	No. of Human-Human BMs	No. of BMs relevant to Machine-Human and not adjusted	No. of BMs relevant to Machine-Human and adjusted	No. of BMs not relevant to Machine-Human	No. of BMs added
Closed-Loop Communication	Exchanging information	10	8	2	0	1
	Giving instructions	4	3	1	0	0
	Providing feedback to other human team members	4	1	1	3	0
Decision-making	Selecting and following regulations and procedures	2	1	0	1	0
	Identifying and selecting options	7	2	2	3	0
	Reviewing course of action	3	3	0	0	0
	Recognition Primed decision-making	1	0	0	1	0
Leadership	Setting and maintaining a team atmosphere	7	0	0	7	0
	Co-ordinating activities	9	0	0	9	0
Performance Monitoring	Monitoring the performance of other human team members	3	1	2	0	0
Backup behaviours	Recognising and assisting when a teammate is overloaded	4	0	2	2	0
Adaptability	Ability to adjust behaviour	8	1	2	5	0
Situational Awareness	Gathering information	5	1	0	4	0
	Comprehending informational elements	4	3	1	0	0
	Anticipating future states	6	2	0	4	0
Shared Mental Models	Understanding roles and responsibilities of self and human team members	2	1	0	1	0
	Understanding roles and limitations of machine team members	0	0	0	0	0
Trust	Demonstrating appropriate levels of trust	0	0	0	0	0
Total		79	29	13	38	1

## 7.3 Results

### 7.3.1 Behavioural Markers System Overview

Table 7.5 shows some examples of the positive and negative human-machine and machine-human behavioural markers, for the full list of behavioural markers see Appendix F. To provide an initial validation of the behavioural markers for the three categories, human-human, human-machine and machine-human interactions, they were then reviewed by two subject matter experts involved in the training of MASS operators and the development of future standards and competencies for operators. The two subject matter experts had 23 and 14 years of maritime experience respectively and had approximately 300 and 400 hours of MASS operational experience.

Table 7.5 - Examples of positive and negative behavioural markers from a range of behavioural categories from the MBS for HMTs for human-machine and machine-human interactions.

Category	Sub-category	Human-Machine/ Machine-Human	Positive Behavioural Marker	Negative Behavioural Marker
Closed-Loop Communication	Exchanging Information	Human-Machine	Provides the necessary information to the machine teammate in a timely manner (e.g., adds in a navigational hazard not marked on the electronic chart so that the navigation system has time to replan the route)	Fails to provide the machine teammate with information or provides that information to them too late.
		Machine-Human	Shares relevant information proactively in an integrated way for the operator to interpret	Does not share relevant information, or shares the information late or the information is not integrated when its shared
Decision-making	Reviewing Course of Action	Human-Machine/ Machine-Human	Confirms with other team members what has happened and whether it has met decision goal	Shows unwillingness to revisit decision or confirm whether a decision has met the goal

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Performance Monitoring	Monitoring the performance of other team members	Machine-Human	Identifies potential mistakes made by the operator	Does not spot errors made by the operator
		Machine-Human	Keeps an eye on other team members' tasks in order to spot possible errors or signs of overloading	Fails to identify the operator's errors
Backup behaviours	Recognising and assisting when a teammate is overloaded	Machine-Human	Recognises that the operator is overloaded and recommends that the system takes back certain tasks	Does not identify that the operator is overloaded and fails to recommend taking back any tasks
		Human-Machine	Takes the appropriate actions when the MASS' systems are out of their operational limits (e.g., the environmental conditions are out of limits, or the traffic density is too high)	Fails to take or does not take appropriate actions when the MASS' systems are out of their operational limits
Adaptability	Ability to adjust behaviour	Machine-Human	Is able to perform alternative actions if new information comes in during operations	Unable to adapt plan with new information
		Machine-Human	Is ready for potential obstacles and negative outcomes during an operation	Does not have the ability to adapt if there are potential obstacles or negative outcomes
Situational Awareness	Gathering information	Human-Machine	Monitors systems regularly to get relevant information for their tasks and ensure awareness of warning indicators (the frequency of the monitoring will depend on the MASS system and operation)	Sporadically scans user interfaces or underutilises systems when gaining awareness (the frequency of the monitoring will depend on the MASS system and operation)
	Comprehending informational elements	Machine-Human	Shows awareness of risks inherent in each action taken	Demonstrates an incomplete or inappropriate awareness of risk

Shared Mental Models	Understanding roles and responsibilities of self, human team members	Machine-Human	Understand the role of other human team members and how their work integrates with their own	Fails to understand the roles and responsibilities of their human team members and how it integrates with their work
Trust	Demonstrates an appropriate level of trust	Human-Machine	Evaluates recommendations from the automated systems' before accepting or rejecting them	Accepts recommendations from the system without fully assessing whether the suggestion is the correct course of action or rejects the recommendations without the appropriate consideration
		Human-Machine	Uses multiple sources of information to inform their decisions	Solely relies on one information source and fails to cross reference the information with other sources

### 7.3.1.1 Closed-loop Communication

Closed-loop communication has been defined as exchanging task-relevant information with other human team members and ensuring information has been received and understood (Salas et al., 2005). It has three sub-categories within the BMS, exchanging information, giving instruction and providing feedback. For exchanging information, all the sub-categories applied to machine-to-human interactions, although the application of the behavioural marker may be slightly different to a human teammate. It will be necessary to consider how the system will communicate clearly and openly, what level of communication is needed and how the system shares its intent before making a decision. In addition, the system will need to communicate a hazard promptly and be able to request information from relevant sources when required. A behavioural marker was added within exchanging information to ensure that the system is sharing information proactively and that the information being shared is integrated to provide the communication operator will need to maintain their SA. This behavioural marker was added as many of the other behavioural markers from human-human teams were related to requesting and receiving information rather than sharing information.

### 7.3.1.1 Decision-making

Similarly to decision-making in human-human teams, the operator will need to be able to make decisions with the system as a team and therefore be able to consider relevant system information

when making decisions. Many of the behavioural markers for decision-making were relevant for machine teammates, such as considering alternate solutions, providing task-relevant information to contribute to team decision-making and ensuring agreement on the course of action when appropriate.

#### **7.3.1.2 Leadership**

The behavioural markers for setting and maintaining a team atmosphere were found to not apply to a HMT, as the behaviours are not ones that a machine can show. However, the operator will need to coordinate the activities with their machine teammate for example, they will need to be aware of the system's abilities and how they can be incorporated into the operation, overseeing its activities and understanding how its decision-making fits into the wider team's decision-making process.

#### **7.3.1.3 Performance Monitoring**

A key behaviour for operators will be their ability to monitor the automated system's performance, similar to performance monitoring within a human-human team, the operator will need to recognise when the system is making errors and have an awareness of what the system's cues are when it is out of its operational limits. The system will also need to monitor the operator's performance, anticipate the operator's actions, identify any mistakes made by the operator and provide feedback to them to facilitate self-correction.

#### **7.3.1.4 Backup behaviours**

In addition to the operator being able to monitor the automated system for its performance, for an HMT to work effectively the teammates will need to provide each other support like in a human-human team where a teammate would take over certain tasks (Begerowski et al., 2023; Roberts et al., 2022; Salas et al., 2005). Operators will need to provide backup to the MASS systems when they recognise the system is out of its operational limits and take the required actions for the situation.

Although a machine teammate will not have the same type of workload issue as an operator, the system will still have its limitations during an operation which an operator will need to be aware of and take action if required. In such situations where possible, the system will need to identify situations where the operator needs to be requested to assist. For example, for a collision avoidance system, an alert may be given to the operator when the maximum number of vessels is exceeded. Machine teammates could be designed to recognise or estimate an operator's workload and then adjust the allocation of tasks between the operator and system to redistribute the workload, either to reduce or increase the operator's workload as needed allowing them to provide the backup behaviours.

#### **7.3.1.5 Adaptability**

The behavioural markers for an operator working within an HMT were the same as for an operator working in a human-human team, as they will still need to show the same ability to adjust their strategies based on the information and situation (Salas et al., 2005). However, many of the behavioural markers were not relevant to a machine teammate, although a system will need to be ready for potential obstacles, be aware of changes occurring and be able to respond to those changes.

#### **7.3.1.6 Situational Awareness**

In the case of MASS operations SA will be distributed between each team member, who will each have their own perception, comprehension and projection of the situation (Stanton et al., 2006). The behavioural markers for an operator in an HMT were adapted as MASS operators will be forming their SA from the system information rather than the external environment as they are operating from RCCs. Therefore, for gathering information operators will need to monitor their user interfaces to maintain an awareness of the present state of the vessel (i.e., its location, speed) and the MASS' environment, rather than using cues in their external environment. Many of the comprehending informational elements and anticipating future states behavioural markers were applicable without being adjusted. However, some markers were adjusted to include suggestions from the systems when planning for contingencies and being able to recognise when the system information is erroneous, which will be a key task for operators to ensure that the MASS systems are operating correctly.

#### **7.3.1.7 Shared Mental Models**

To operate effectively as an HMT, the teammates will need a shared mental model to understand what their tasks and roles are as individual teammates and also what the functions and roles of their teammates are (Gisick et al., 2018; Salas et al., 2005). The system's ability to communicate effectively will be key to developing and maintaining the team's mental model, so the teammates can have an awareness of what the other is doing (Stowers et al., 2021). Therefore, the behavioural marker for showing an understanding of the role and tasks of their human teammates is still applicable to a machine teammate. Having a shared mental model between the teammates is required so that the teammates can understand how to support their teammates by predicting their needs and behaviours (Salas et al., 2008).

#### **7.3.1.8 Trust**

Types of observable behaviour that operators could be assessed on for appropriate trust are operators engaging the automation in the correct situations and whether they are selecting the right

levels of control to operate the MASS safely (Dreyer and Oltedal, 2019; Hogg and Ghosh, 2016; Lee and See, 2004). Other behaviours operators will need to show are that they are evaluating the recommendations from the system and over-trusting the system and blindly accepting them or under-trusting the system and rejecting the recommendation without considering it (Parasuraman and Riley, 1997; Walliser et al., 2016). Another key behaviour for MASS will be the operator using multiple sources of information to inform their decisions and not trusting single sources when operating from RCCs as one source could be faulty (Palbar Misas et al., 2024).

### **7.3.2 Human-Machine Teams Observations**

To provide an initial validation of the human-machine and machine-human behaviours, naturalistic observations were undertaken in an RCC where Uncrewed Aerial Vehicles (UAVs) were being operated. These observations were conducted to investigate the behaviours seen during UAV test flights from the HMT teammates. UAV observations were used to validate the behaviours as their operation shares similarities with MASS and because of the limited access to MASS operations as their operation is relatively new. For further details of the similarities and differences between MASS and UAV operations see section 2.1.1. In summary, the similarities between UAV and MASS are that both are operated from user interfaces from an RCC, and they use automated control systems so the operator's role is primarily supervisory.

The study received ethical approval from the University of Southampton ethics board (Ethics ID: 66870). Two series of test flights were observed and recorded using two cameras to capture behaviours in the RCC and the interactions of the operators with their interfaces. The first series of test flights lasted an hour and involved flights with three UAVs operating from the same RCC. In this first set of flights in the RCC, there were three UAV operators each responsible for a single UAV and an RCC supervisor oversaw the test flight. In the second series of test flights which also lasted an hour, only one UAV was being operated, so there was one operator, a payload operator and the RCC supervisor in the RCC.

The observational recordings were then reviewed iteratively to analyse the types of human and machine behaviours seen during the two test flights. First, the human behavioural markers were assessed on whether that had been seen during the test flights. Then if the behaviour had been observed the frequency of the behaviour was recorded and an example of the type of behaviour for that behavioural marker was noted. The same procedure was then followed to analyse the machine behaviours against the machine behavioural markers, to record which behaviours had been observed their frequency and examples of the system's behaviour.

### 7.3.2.1 Behavioural Observation Results

Table 7.6 shows the results of the observations of the UAV test flights, the number of human-machine and machine-human interaction behavioural markers seen and not seen, and the frequency of the seen behaviours. For the human-machine interactions, approximately 38% of the behaviours were observed, with the behaviours seen in closed-loop communication, decision-making, leadership, performance monitoring, adaptability, SA and trust. Most of the behaviours were observed in the sub-category gathering information, selecting and following regulations and procedures, giving instructions, ability to adjust behaviour and demonstrates appropriate levels of trust.

For the machine-human interactions, behaviours were only seen in three categories, closed-loop communication, performance monitoring and SA and 24% of the total behaviours were observed. Many of the behaviours within exchanging information and giving instruction categories were seen. This may be due to the type of system and the operation being carried out, as the system's main tasks were communicating its tasks and acknowledging the instructions given by the operator. The system could monitor the operators' performance as it could identify mistakes made by the operator such as validation checks for landing waypoints and give the operator clear feedback on which parameters needed to be adjusted to correct the issue.

No behaviours were seen in the shared mental models category, the backup behaviours category, and the sub-categories anticipating future states and recognition primed decision-making for either human-machine or machine-human interactions. Behaviours may not have been observed within these categories and sub-categories as the operations were not abnormal operations during the test flights. Therefore, the automation stayed within its operational limits and the operator did not need to intervene. Also, the system was using high levels of automation (e.g., it used an auto-pilot function that completed all the navigation, take-off and landing) but it was not advanced enough to have an awareness of what the human operator actions were and how they integrated with the overall team goal.

Table 7.6 - Behaviours from the BMS seen from the observations of the UAV test flights and the frequency at which each behaviour was seen. (Note: Human-Machine interaction (H-M), Machine-Human interaction (M-H), Behavioural Marker (BM))

Main Category	Sub-category	No. of H-M BMs seen	No. of H-M BMs not seen	H-M BMs freq.	No. of M-H BMs seen	No. of M-H BMs not seen	M-H BMs freq.
Closed Loop Communication	Exchanging information	2	2	7	4	7	51
	Giving instructions	3	0	6	2	2	34

	Providing feedback to other human team members	1	0	5	1	1	9
Decision-making	Selecting and following regulations and procedures	2	0	11	0	1	0
	Identifying and selecting options	2	5	3	0	5	0
	Reviewing course of action	0	3	0	0	3	0
	Recognition Primed decision-making	0	1	0	0	1	0
Leadership	Co-ordinating activities	1	1	2	-	-	-
Performance Monitoring	Monitoring the performance of other human team members	1	0	1	2	0	3
Backup behaviours	Recognising and providing assistance when a teammate is overloaded	0	3	0	0	2	0
Adaptability	Ability to adjust behaviour	2	6	6	0	3	0
Situational Awareness	Gathering information	4	2	27	1	0	0
	Comprehending informational elements	1	3	2	0	3	0
	Anticipating future states	0	6	0	0	2	0
Shared Mental Models	Understanding roles and responsibilities of self, human and machine team members	0	4	0	0	1	0
Trust	Demonstrating appropriate levels of trust	3	3	6	-	-	-
Total		20	33	58	10	31	97

## 7.4 Discussion

A novel BMS has been developed for HMTs, which has included behavioural markers for machine teammates, to ensure system designs aid collaboration and coordination within the HMT. In addition, behavioural markers were also suggested for human teammates interacting with machine teammates. Whilst BMS are often used to assess human performance in safety-critical domains, the development of behavioural markers for HMTs has shown the types of behaviours that need to be considered during the design of systems and how these designs can be evaluated from both the human to machine and machine to human interaction perspectives (da Conceição et al., 2017; O'Connor et al., 2002; O'Connor, 2011; Saeed et al., 2017).

The findings show that many of the competencies from human-human teams are required for HMTs, which is similar to Stowers et al. (2021) findings that to optimise the performance of HMTs, machine teammates need teamwork competencies like those of human teams. Whilst there are issues in

applying human teamwork models and models for HMTs due to the differences in capability between the human and machine teammates, the development of the BMS has demonstrated that many of these behaviours are applicable even though how the behaviours would be designed into a system would differ from human behaviour (Joe et al., 2014; Roberts et al., 2022).

The UAV observations provide an initial validation for the BMS as behaviours were seen in seven out of the nine main behavioural categories for the human-machine interaction behaviours and 38% of the total human-machine interaction behaviours were seen. This demonstrates that some of the behavioural markers are relevant for analysing human-machine interactions and these behaviours occur within HMT at an RCC. However, further work will be needed to validate the BMS fully and explore whether the behaviours not seen are relevant to other systems and operations. For the machine-human interactions, behaviours were observed in three out of seven relevant behavioural categories and 24% of the behavioural markers were observed. This suggests that further validation is needed to investigate whether the other behaviours from the HMT BMS are observed in RCC teams. Further observations could include longer observational times, abnormal operations and other types of automated systems. However, it does provide a start to validating the BMS for its applicability to assessing a machine teammate using observable markers, as it shows that these types of behaviours are seen in RCC team operations. Behaviours were not observed for shared mental models and backup behaviours, and many were not seen within the adaptability category. However, these types of behaviours would not have been expected to have been observed during normal RCC operations. Similarly, few of the decision-making behaviours were seen from the operator, and none were seen from the system. The limited number of decision-making behaviours seen may have been due to the lack of complexity of test flight, as neither the operator nor the system needed to respond dynamically to a situation. It also could have been due to the fact the system was not designed to display all of the machine behaviours identified in the BMS, suggesting they could be included in future designs.

The development of the BMS for HMTs has shown that many of the same concepts still apply to achieve optimal performance in the team, even if how the behaviour is achieved differs between human and machine teammates. The BMS has included additional behaviours that human operators will need in HMTs, which has also been discussed by Dubrow et al. (2024) that the human teammate's competencies will need to be considered as well as the design of systems. The BMS could be incorporated into the future operators' Bridge Resource Management training or the equivalent that is developed for MASS operators to support team training in addition to evaluating individual performance (Fjeld and Tvedt, 2020; Praetorius et al., 2020). However, whilst training may be used to improve HMT performance, first it will be necessary to consider the system's design, as non-technical skills training should be used as the last consideration for improving safety (Flin et al., 2008; Young and Steel, 2017). The machine behaviours suggested in the BMS can be used to reduce

the training burden for operators by making the systems more intuitive for users by considering the teamwork behaviours humans require.

#### **7.4.1 Closed-loop Communication**

Closed-loop communication was found to be one of the HMT BMS behavioural categories as these types of communication behaviours are necessary to promote teamwork within the HMT. However, when a machine teammate displays positive communication behaviours, it has been shown that it can still lead to negative performance (Demir et al., 2016). This negative performance may have been due to system failure and a lack of human-like behaviour of the machine teammate, so it will be necessary to consider how the behaviours in the BMS can be designed into a system to make them more human-like (Demir et al., 2016). It has been previously shown that HMT performance can be improved by changing a system's communications behaviour and style (Johnson et al., 2023; McNeese et al., 2018). These system communication changes can increase an operator's ability to anticipate their teammates' information needs and share information more pre-emptively (Johnson et al., 2023; McNeese et al., 2018). Demonstrating the importance of designing appropriate communication behaviours into a system (Johnson et al., 2023; McNeese et al., 2018). Further development is required to improve system designs to increase a machine teammate's effectiveness at communicating with operators (McNeese et al., 2018). This shows the need to consider how these behavioural markers can be applied in system design. When interacting with an automated system via an interface, operators have suggested that making the dialogue more human-like could improve team-building effects (Tokadlı et al., 2021). Therefore, it is necessary to consider how the teamwork behaviours included in the HMT BMS could be used to make the interactions more human-like.

To improve exchanging information in an HMT the use of multimodal interactions has been suggested, for example, having a written record to refer to if a verbal cue is missed (Tokadlı et al., 2021). Similarly, the use of the correct medium for communication was found as a behavioural marker for machine teammates (Tokadlı et al., 2021). Similarly, other findings have suggested that additional modalities to visual, such as audio-voice communication might be appropriate to increase the operator's perception of teaming by making the communication more human-like (Bogg et al., 2021). Another exchanging information behaviour for machine teammates in the BMS was promptly warning the operator of any hazards. It has been shown that providing information early can improve a system's ability to share information more effectively and the operator's response to an automation failure (Johnson et al., 2023). However, how the communicated information is presented should be considered to ensure its supporting team coordination when exchanging information (Lakhmani et al., 2022). Bogg et al. (2021) suggested four communication types, acknowledgements, advice, information and warnings. These communication types are all included within the three communication sub-categories from the BMS, which suggests that the sub-behavioural categories

capture the types of communications required in an HMT. Providing feedback to team members was also included within the communication category of the BMS, which is supported by Tsamados et al. (2024) finding that effective channels and loops for feedback between the human and machine agents is a key requirement for an HMT.

### **7.4.2 Decision-making**

The development of the BMS showed that the system will need to contribute to the decision-making process of the HMT and review the course of action with the other teammates. Bidirectional transparency has been suggested to allow the teammates to understand each other's reasoning for their decisions (Chen et al., 2018). This would aid them in contributing to the team's decision showing the importance of the system and operator being able to show collaborative decision-making behaviours (Chen et al., 2018). To support a machine teammate in performing collaborative decision-making, the team will require a shared mental model which again highlights the importance of this behaviour, as otherwise, the decision-making of either teammate on their own may be ineffective (Cannon-Bowers et al., 1993; Grimm et al., 2023). For machines it has been suggested for them to become teammates they will need to engage in complex decision-making (Seeber et al., 2020). Therefore, an important competency for operators will be ensuring they understand how the system's decision-making process fits in with the wider team and overall team goal (Seeber et al., 2020). However, as shown in this BMS the system design will need to consider how to share the system's decision-making with the operator to achieve this behaviour.

### **7.4.3 Leadership**

The development of the BMS showed that not all the human-human behavioural markers can apply to working within an HMT. For example, the markers in the setting and maintaining a team atmosphere category did not apply to human-machine interactions, e.g., modifying behaviours to take in the current emotions of team members, as this will not be necessary for their machine teammates. This limitation of machine teammates has previously been discussed as currently machine teammates have not reached emotional intelligence so they are unable to set a team atmosphere, as they lack the 'soft skills' to improve the morale or confidence of human teammates (Joe et al., 2014; Smith and Green, 2018). It has been discussed that leadership is a key behaviour for the safe operation of MASS as found in the development of the BMS (Kim and Mallam, 2020). However, it has been suggested that there is a difference in which current mariner leadership competencies will be more important (Kim and Mallam, 2020). A framework for a human leader of an HMT has been outlined by Flathmann et al. (2021), which has similarities to the BMS leadership behavioural markers, both highlight the need to coordinate the team's activities and manage the team's resources and information. Although leadership within an HMT differs from traditional human

leadership, there is still a need to understand what leadership behaviours will look like in an HMT (Flathmann et al., 2021; Kim and Mallam, 2020).

### **7.4.4 Performance Monitoring**

Operators will be responsible for monitoring the performance of their machine teammate, however, to support the behaviours identified within the BMS it is necessary first to consider the system design and how their machine teammate can be designed to support such behaviours. To support performance monitoring it has been suggested that increasing the system transparency will aid operators in effectively monitoring the system and evaluating its functioning (Ramos et al., 2019; van de Merwe et al., 2022b). To support their ability to monitor the system's performance operators will require training on the automated system's limitations to know what cues to look for and recognise that its operational limits have been reached (Meštrović et al., 2024).

Performance monitoring has also been considered in the design of aviation automation, as a system could flag when an operator's inputs are inconsistent, which like the BMS shows that promoting coordination is a relevant behaviour in an HMT (Burian et al., 2023). It has been found that machine teammates' behaviour can reduce the team's efficiency compared to a human-human team if they cannot anticipate the needs of their human teammates, showing the importance of their ability to monitor the operator (McNeese et al., 2018). Even though a machine teammate may not be able to monitor the performance of a teammate in the same way as a human, this behaviour is still key to the functioning of the team as shown in the BMS. It has been suggested systems could gain the ability to monitor their human teammate by using technologies such as artificial intelligence (Mehak et al., 2024). It has been proposed this performance monitoring behaviour could be achieved using action recognition to give the system the ability to understand and interpret an operator's actions (Mehak et al., 2024).

### **7.4.5 Backup Behaviours**

The requirement for automated systems to provide backup behaviours through feedback and offers of assistance has previously been suggested for the design of future aviation systems, which demonstrates the utility of the BMS for designing MASS systems but also that it could be applied to other safety-critical domains (Burian et al., 2023). Additionally, for a machine to display this behaviour it has been highlighted that is important for a system to have an accurate shared mental model, so it can anticipate what backup their human teammate needs (Matthews et al., 2021). However, further investigation is needed to determine the details of how these backup behaviours should occur between human and machine teammates to mimic that behaviour (Roberts et al., 2022). A machine behavioural marker suggested in the developed BMS was to give the system the

ability to recognise when the operator has a high workload and adjust the allocation of tasks to reduce their workload. Concepts to estimate an operator workload have been suggested for applications in disaster relief and remotely piloted aircraft and they will need to be further investigated to investigate how they could be applied to MASS and validate the concepts (Giolando and Adams, 2024; Heard and Adams, 2019).

### **7.4.6 Adaptability**

The development of the BMS has shown that some of the behavioural markers within the category adaptability apply to systems, as systems will need to be designed to be adaptable to the internal and external environment. It has also been suggested that not only should machine teammates be able to adapt to changes in their environment but also be able to adapt to their human teammates (Zhao et al., 2022). It has been discussed that adaptability is a strength of human teammates versus machine teammates who, whilst consistent in their ability to perform tasks, machines are often unable to improvise in unforeseen situations and, therefore, may be less able to show adaptable behaviour (Madni and Madni, 2018). However, within the HMT, the different strengths of the teammates can be utilised to improve the overall performance of the team, highlighting the need for both the sets of human and machine behavioural markers (Madni and Madni, 2018). It has also been discussed that the development of a shared mental model between the members of the HMT will be needed to support each teammate's ability to adapt to a changing situation (Tsamados et al., 2024).

### **7.4.7 Situational Awareness**

For the system's SA behaviours, the system will need to be able to identify a change in the environment and communicate that change to the operator, show a clear account of the current situation, and show an awareness of the risks inherent in each action and plan for contingencies. Similarly, McNeese et al. (2021) suggested that it will be necessary to ensure that a machine teammate can be designed for adequate distributed SA, otherwise the erroneous will be on the human operator to develop the SA for the team and could cognitively overload the operator. In addition, operators will need to be supported through the system design due to the remoteness and high levels of automation making it more difficult to maintain SA, as discussed in Chapters 3 and 4 (Man et al., 2014).

### **7.4.8 Shared Mental Models**

The need for a shared mental model within an HMT has been discussed as a key part of an HMT's ability to work effectively, showing the importance of considering this behaviour (Andrews et al., 2023; Grimm et al., 2023). It has been suggested that there are potential difficulties in achieving a

shared mental model within an HMT due to the complexity of representing the team as a model in addition to creating a task model (Andrews et al., 2023). A machine teammate would need both a task model and a team model, as shown in the behavioural markers, as the system will need to understand the operator's tasks and how they integrate with their own (Andrews et al., 2023). Artificial intelligence has been used to develop a representation of a human teammate's mental model to facilitate a shared mental model, suggesting for future MASS systems, such technologies could aid in displaying the shared mental model behaviours outlined in the BMS (Grimm et al., 2023). Another issue for shared mental models within an HMT is whether systems should be designed first and then operators should be trained to adopt a compatible mental model with their teammate, or whether a system should be configurable to conform to the human's mental model, further work is needed to explore the approaches (Grimm et al., 2023; Matthews et al., 2021). However, the development of the BMS has shown that the system design should consider how to give the system the ability to understand how the operator's work integrates with the system's work.

### **7.4.9 Trust**

Trust was added to the BMS as it will be an important factor in how operators can work effectively with MASS systems (Barrett-Pink et al., 2019; de Rosa and Strode, 2022; Hogg and Ghosh, 2016). The types of behaviours included in the BMS category for trust have been discussed as key behaviours to ensure MASS are operated safely such as engaging the automation at the right times and using the appropriate levels of control (Dreyer and Oltedal, 2019; Hogg and Ghosh, 2016). It has been shown that many factors can influence an operator's trust in an automated system (Hoff and Bashir, 2015; Schaefer et al., 2016) and therefore they could be considered in the design and development of future automated systems to ensure the appropriate behaviours are seen. However, using behavioural markers to evaluate trust has many limitations and there are multiple ways of measuring human-machine trust beyond using behavioural observation and would need to be used during the design of a system (Geburu et al., 2022). The other factors involved in trust in the operation of uncrewed MASS are explored in further detail in Chapter 5, including design and training principles for promoting calibrated trust in HMTs. It is still necessary to include trust within the BMS for HMTs as it plays a key role in teamwork, particularly the HMT's ability to communicate effectively, the BMS is just limited to exploring trust in terms of a smaller number of observable behaviours (McNeese et al., 2019; Stowers et al., 2021).

### **7.4.10 Future Work and Evaluation**

It will be necessary to explore what other behaviours could be used to assess machine and human teammates that might be specific to only HMTs, to extend the BMS developed here. Additional observations of MASS operations will be needed to validate the behaviours not seen during the UAV

observations such as backup behaviours and some of the decision-making and adaptability behaviours which are more likely to be seen during abnormal operations and to explore if there are any other teamwork behaviours specific to HMTs. However, the UAV observations do show an initial validation for the BMS. There are limitations to using behavioural markers to assess as observer ratings can be biased and influenced by primacy and recency effects and during operators' training appropriate objective measures could be used in conjunction with the behavioural observation to assess performance (Roberts et al., 2022). The behavioural markers can be used to evaluate the performance of an HMT at a team level rather than just focusing on the individual performance of team members, unlike some other measures (Roberts et al., 2022). Further work will be needed to explore how these behaviours can be effectively integrated into the design of machine teammates, such as how machine teammates can monitor the performance of their human teammates and provide helpful assistance. The types of communication that are most effective for different tasks during the operation of MASS also need to be investigated. As the application of these behaviours will differ from humans the design of these behaviours will need to be investigated to understand how they can optimise teamwork within HMTs.

### **7.5 Conclusion**

A BMS has been developed for the operation of MASS from RCCs, including behavioural markers that can be used to design and evaluate a system's ability to interact with an operator to promote teamwork and to assess an operator's interactions with the system. The BMS is also being used to inform the development of new national and international training standards and competencies for MASS operations and to support operators' training for the new ways of working with MASS. As higher levels of automation are used in the design of MASS, which is changing the nature of the interaction between the operator and system, it is necessary to consider the development of non-technical skills for working effectively within an HMT as well as their human teammates within an RCC.

The developed BMS for HMTs has shown that many of the teamwork behaviours from human-human teams still apply to the relationships within an HMT. Although some of the behavioural markers did need adjusting to be relevant for human-machine interactions. The UAV observations showed that some of the behaviours within the BMS can be observed within HMTs and it provides a starting point for validating the BMS. However, this initial validation was limited due to the complexity of the scenario and that the scenario being observed was normal operations, future validation using abnormal operational scenarios will be required to investigate if the other human and machine behaviours are observed when HMTs operate from RCCs. Further work will need to investigate how

the behavioural markers for machine teammates could be applied in more detail to the design of future MASS systems to ensure systems can display these teamwork behaviours.

The next chapter applies a sociotechnical systems approach to investigate decision-making in MASS more broadly, to build upon the analysis of the previous thesis chapters which have focused on lower levels of the MASS system, e.g., the MASS operator and their HMI. This sociotechnical system analysis will be used to explore the accountability of the decision-makers within the wider MASS system, as it is a factor within the decision-making factors in HMT model and the approach will include the higher levels of the system.



# **Chapter 8 The application of a system-based risk management framework and social network analysis to the Maritime Autonomous Surface Ship system: Who are the decision-makers in the wider system?**

## **8.1 Introduction**

The research so far has focused on lower levels of the sociotechnical, particularly focusing on how system design can support MASS operator's decision-making. However, as MASS is a sociotechnical system Chapter 8 also explores the higher levels of the MASS system. This chapter aims to use a sociotechnical systems approach to analyse the MASS system to understand who the actors are within the system and their dynamics to build upon the findings in the previous chapters which have explored how to support the MASS operator's decision-making. This approach has been used as accountability is a factor in the decision-making factors in HMT model but as discussed in Chapter 2 there is a need to view accountability across the actors of the system rather than focusing on the operator. The analysis of the sociotechnical system shows how recommendations can be made at each level of the MASS system.

### **8.1.1 MASS certification and regulation**

There are various MASS that are currently operational, for examples see Chapter 1, section 1.1. However, there are currently no formal regulations or standards that have been developed specifically for MASS, which brings concerns for the safety of their operation (Amro et al., 2020; Komianos, 2018; Nzengu et al., 2021). Although MASS is expected to bring safety benefits by removing human involvement in parts of the system, removing factors such as fatigue and boredom and the automation has the potential to perform tasks more reliably, if they are not regulated appropriately they may bring in new hazards (Hoem et al., 2018; Kim and Schröder-Hinrichs, 2021). As MASS use higher levels of automation due to the advancements in technology, there is a potential to introduce new errors and risks to the system (Hoem et al., 2018; Kim and Schröder-Hinrichs, 2021; Lützhöft and Dekker, 2002). Therefore, it will be important that MASS have an appropriate regulatory framework in place to support the safe development and operation of MASS.

## Chapter 8

The International Maritime Organisation (IMO) is a specialised agency of the United Nations (UN) responsible for developing international shipping regulations and standards for improving safety, sustainability and security in international shipping (International Maritime Organisation, 2023). The IMO consists of an Assembly, Council, five main committees (Maritime Safety, Marine Environment Protection, Legal, Technical Cooperation and Facilitation) and several sub-committees, where international regulations and standards are created or amended (International Maritime Organisation, 2023). The IMO currently has 175 member states who participate in its meetings including the UK, each member state can ratify the convention or standard into their national law so they can be enforced by that member state (International Maritime Organisation, 2023).

A regulatory scoping exercise for the use of MASS has been conducted by the IMO, as a first step to developing a regulatory framework for them (International Maritime Organisation, 2018; Jo et al., 2020a). As part of the regulatory scoping exercise the IMO's Maritime Safety Committee (MSC) has reviewed the different IMO legal instruments to determine: whether they applied to MASS and whether they prevented MASS operations; whether they applied to MASS and did not prevent operations and required no actions; or they did apply and need to be amended or clarified and/or may contain gaps; or have no application to MASS operations (International Maritime Organisation, 2018; Jo et al., 2020a). This involved reviewing various safety treaties such as the Safety of Life at Sea (SOLAS) Convention, 1974; Standards of Training, Certification and Watchkeeping for Seafarers (STCW), 1978 and the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG) as well as regulatory instruments (International Maritime Organisation, 2018; Jo et al., 2020a).

The outcome of the regulatory scoping exercise was discussed and completed by the MASS Working Group which met during MSC's 103<sup>rd</sup> session in May 2021 (International Maritime Organisation, 2021; Shiokari, 2020). Common issues with the IMO instruments were the definitions relating to seafarers such as master, crew and responsible person, as these would need to be defined for remotely operated and autonomously controlled ships (International Maritime Organisation, 2021; Shiokari, 2020). These definitions will be important to establish what the responsibilities of those involved in operating the MASS are, even though these roles are no longer on board the ship. The findings showed there was a lack of requirements for RCCs and the personnel that will be working at RCCs (Shiokari, 2020). The development of requirements for the personnel working at RCCs will be needed to ensure that MASS are operated at levels at least as safe as manned vessels. Another identified gap was the requirements for onboard systems and equipment, especially for systems that

require manual operations such as firefighting and life-saving equipment (International Maritime Organisation, 2021; Shiokari, 2020).

Although there is no formal legal framework for MASS specifically at present, organisations such as, Maritime UK have published a voluntary industrial code of practice for MASS up to 24 m in length, to provide practical guidance for the design, construction and safe operation of MASS (Maritime UK, 2020). It is worth noting that even though there is no formal regulatory framework, MASS must still comply with existing regulations where they are relevant. The UK code of practice was prepared by the Maritime Autonomous Systems Regulatory Working Group (MASRWG), which included: national organisations (e.g., British Marine, National Oceanography Centre), classification societies (e.g., Lloyds Register EMEA and Bureau Veritas) and organisations from industry who design and develop MASS (Maritime UK, 2020). Currently, to be issued with a certificate for its particular operation a MASS must comply with all the requirements in the code of practice relevant to its MASS class (which depends on its overall length and maximum speed and the MASS' operating area) (Maritime UK, 2020). The code of practice has been reviewed by the Maritime Coastguard Agency (MCA) but the MCA has said it would require further investigation to publish the code of practice and it would also be dependent on any regulations and standards produced by the IMO (Maritime UK, 2020). Whilst there is no primary legislation for MASS to operate in the UK and under the UK flag, the MCA relies on the exemption available in The Merchant Shipping (Load Line) Regulations 1998 to certify MASS (Department of Transport, 2021). In addition to the MASRWG UK code of practice, recognised classification societies have also produced technical codes for the design, build and maintenance of MASS, such as Lloyd's Register Unmanned Marine Systems (UMS) code which was launched in 2017 to allow owners and operators to achieve certification that is acceptable to regulators and local authorities (Lloyd's Register, 2017). SEA-KIT International's MASS was the first MASS to be awarded certification under Lloyd Register's UMS code in July 2021 (SEA-KIT International, 2021). It is useful to investigate the UK MASS system as the UK is a highly influential member of the IMO and other flag states do adopt or modify policies and regulations developed by the UK (Baumler et al., 2021).

The standards and regulations developed by the IMO and other international and national organisations will be important to the safe operation of MASS, as they will feed down to the legislation and regulations implemented by the UK government and regulators. Although the MSC of the IMO has indicated that new regulations could be developed for MASS, this would not be before 2028 (Department of Transport, 2021). It has been highlighted that there is a need to consider the whole system when assessing the safety of maritime systems due to their increasing complexity (Relling et al., 2018). To ensure the safe operation of MASS it will be important to consider the wider

socio-technical system rather than just focusing on the MASS and its operator (Banks et al., 2018b; Stanton and Harvey, 2017). It has been found in other domains such as automated vehicles (Banks et al., 2019) that the introduction of new automated systems can have safety implications and bring regulatory issues. In the automated vehicle domain, it was found that vehicle manufacturers had been largely left to their own devices when it came to designing, testing and marketing some of their automated systems (Banks et al., 2019). The analysis showed that lower levels of the system lacked appropriate support and guidance due to the lack of top-down influence in the system (Banks et al., 2019). Therefore, it will be important to consider what the influences are in the UK MASS system and whether each level has sufficient support and guidance.

MASS are still in an early stage of development, so there are still uncertainties surrounding their operation making it difficult to predict the likelihood and types of failure that might occur (de Vos et al., 2021; Hoem et al., 2019). It is important to consider the potential of maritime incidents due to the introduction of MASS (de Vos et al., 2021; Hoem et al., 2019). It has been suggested that the use of uncrewed MASS will reduce the likelihood of collisions occurring but the severity of these accidents may be higher due to the limited recovery capability if there is no longer any crew on board (Thieme et al., 2018; Wróbel et al., 2017). It will therefore be important to consider how systemic failures could lead to incidents during the operation of uncrewed MASS and what mitigation strategies could be put in place to reduce these risks. There are potentially new failures and uncertainties introduced when operating uncrewed MASS due to their remotely controlled nature (Goerlandt, 2020; Jalonon et al., 2017). An example of this is the possible loss of communications between the RCC and the MASS, if this were to occur then the operator would have no way of communicating with the MASS or have any oversight of its automated systems (Ahvenjärvi, 2016; Burmeister et al., 2014b; Kim and Schröder-Hinrichs, 2021; Ventikos et al., 2020; Wróbel et al., 2017; Wróbel et al., 2018). Also, it has been highlighted that the nature of the operators' work will have changed, so the skills and experience they require to safely navigate from an RCC rather than a bridge will also have changed (Goerlandt, 2020).

Wróbel et al. (2018) applied the System-Theoretic Process Analysis (STPA) to analyse the interactions between the different components in the operation of automated merchant vessels. It was shown that if some of the control actions were inadequate this could lead to failures propagating through the system rapidly due to the potential number of hazards introduced, which shows the need to consider the wider aspects of the MASS system (Wróbel et al., 2018). Relling et al. (2018) suggested that systemic safety models such as Accimap (Svedung and Rasmussen, 2002) and Event Analysis of Systemic Teamwork (EAST) broken-links approach (Stanton and Harvey, 2017) would be appropriate

to assess MASS safety, as these approaches include the wider system, not just sub-components of the system.

This chapter aims to analyse the current MASS system in the UK using the Risk Management Framework (Rasmussen, 1997) and then use Social Network Analysis (Baber et al., 2013; Driskell and Mullen, 2004) to investigate the wider MASS system's dynamics and to make recommendations for the UK MASS system. The approach was selected to analyse the MASS system as it has been suggested that it provides a comprehensive view of an entire sociotechnical system, including those responsible for developing policies and implementing regulations, as well as international and national bodies involved in the system (Parnell et al., 2017; Salmon et al., 2012a). It allows the different processes between the different system levels to be seen including the top-down processes from international, and national bodies and regulators, middle-up processes from industry and bottom-up processes from the lower system levels (Banks et al., 2019). It has also been found that the Risk Management Framework is applicable across multiple domains including the maritime domain (Butler et al., 2022; Kee et al., 2017; Lee et al., 2017; Stanton and Salmon, 2019).

### **8.1.2 Risk Management Framework**

One sociotechnical system approach is Rasmussen's (1997) Risk Management Framework (RMF. See Figure 8.1) which can be used to show the interactions between different system levels. The original RMF hierarchy shown in Figure 8.1 consists of six levels: government, regulators/associations, company (industry), management (resource providers), staff (end users), and work (equipment and environment). It shows how different levels of a sociotechnical system are involved in managing the risks associated with operating that system. Top-down processes from the government writing the laws which are turned into regulations (Rasmussen, 1997). The regulations are then put into company policies for management to give to their staff, who can then use them to promote safe operations (Rasmussen, 1997). The RMF also shows the bottom-up processes in the sociotechnical system, how observations from members of staff get logged by management, which is then fed to the company level through reports (Rasmussen, 1997). These reports are then reviewed by the company and incident reports are reviewed by the regulator and then fed back to the Government to inform the law (Rasmussen, 1997).

## Chapter 8

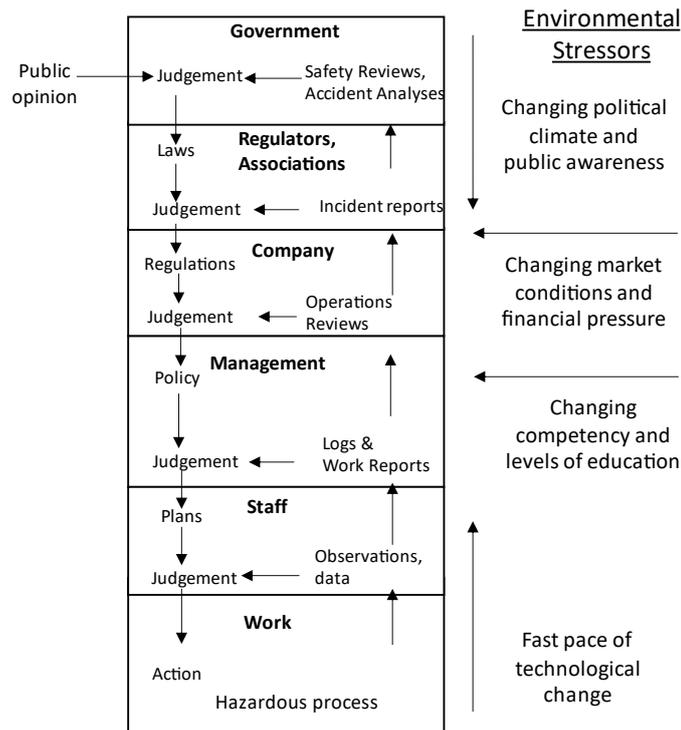


Figure 8.1 - Rasmussen's Risk Management Framework (Rasmussen, 1997).

Parnell et al. (2017) added two additional levels, international and national committees, to show how these committees influence government policies and legislation for in-vehicle technology use. For the application of the RMF to MASS in the UK, it will also be necessary to include these additional levels as international organisations such as the IMO, International Association of Classification Societies (IACS) and national committees such as Maritime UK and the Transport Select Committee, as they all influence how MASS are currently regulated and how they will be in future (Bratić et al., 2019; Department of Transport, 2021; International Maritime Organisation, 2021; Maritime UK, 2020).

Figure 8.2 shows the RMF adapted for the MASS system, it also shows different views of the system: at the micro level there is the human-machine interaction between the end user (the operator) and MASS; at the meso level it also includes the companies operating MASS and the resource providers involved in their operation; at the macro level, it extends the system view to include the regulating bodies (e.g., the MCA), government, national and international committees (e.g., the MASRWG, the IMO) (Klein and Kozlowski, 2000; Verbong and Geels, 2007). The RMF will be used to model the UK MASS system to show the macro system view and to show how each of the hierarchical system levels influences MASS operation, to look beyond just focusing on the micro view of just the operator and the MASS. It will show how the various international and national committees influence the MASS system by generating standards and policies, which are then fed down to

governments informing their policies and developing legislation, this legislation informs the regulators' (Banks et al., 2019; Parnell et al., 2017).

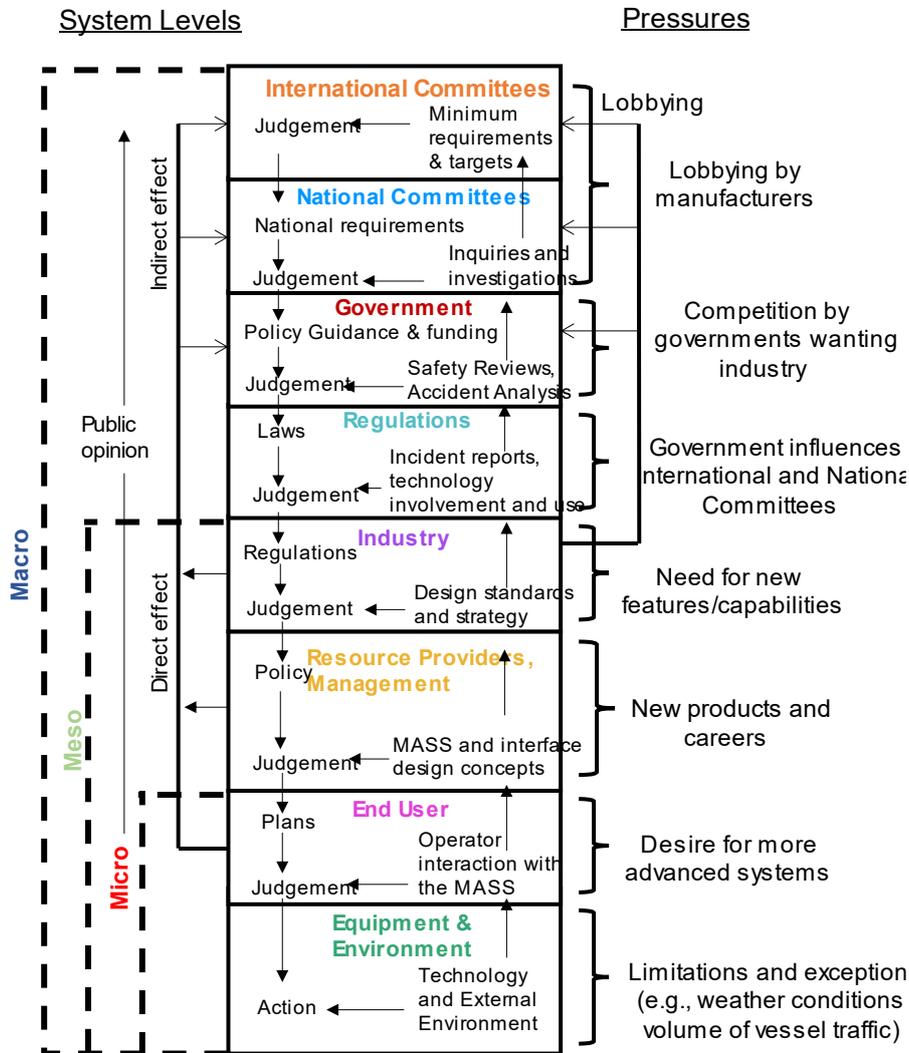


Figure 8.2 - Annotated RMF for MASS implementation (Adapted from Banks et al., 2019).

The regulations developed at these top levels (International Committees, National Committees, Government and Regulators) will then influence the relevant industries developing the systems and the resource providers (e.g., training centres, system architects and human-machine interface designers) in the middle levels of the RMF hierarchy (Parnell et al., 2017). The middle levels of the RMF, the industry and resource providers levels, will then influence the two lowest levels of the hierarchy are the end-users (e.g., MASS operators) and their contextual environment (e.g., the MASS' automated system and the environmental conditions), through policy and guidance to the operators. Within the RMF there will also be bottom-up processes through reporting and feedback

from the equipment and environment levels and end-user levels to the resource providers and industry levels. There are also middle-up processes from the industry level (i.e., MASS manufacturers and technology companies) as the advancements in technology will drive the regulations being developed at the top levels of the hierarchy.

The RMF has previously been utilised in the maritime domain to analyse the Sewol ferry accident in South Korea using the Accimap framework (Svedung and Rasmussen, 2002), it showed how actors and decision-makers at each level of the sociotechnical system contributed to the accident (Kee et al., 2017; Lee et al., 2017). For example, it showed how the lack of an oversight body between the Korean Shipping Association and the Korean Register of Shipping meant that the weight limit of the ferry was not enforced, the Korean Shipping Association had the information on the weight limit and the Korean Register of Shipping had the actual amount of weight the ferry carried but there was no communication between the two to enforce the limit (Lee et al., 2017). The RMF has also been applied to maritime pilotage in New Zealand to understand how pilots make decisions and what factors influence their decision-making (Butler et al., 2022). The RMF was used to show the system level of each of the factors that affect decision-making (Butler et al., 2022). It showed that the system in which the maritime pilots work is highly complex and there are many system-wide factors which affect their decision-making process (Butler et al., 2022). Applying the RMF to the UK MASS system will show what connections there are within the system currently and what links may need to be made to strengthen the system, as the MASS system's regulatory framework is developed. Using this approach will allow suggestions to be made on how to support each level of the MASS system and show where any shortfalls are in the system.

## **8.2 Modelling the UK MASS system using the Risk Management Framework**

The first step of modelling the UK MASS system was to identify the different actors, organisations and decision-makers in the UK MASS system by creating an actor map. Rasmussen's (1997) RMF is often used to analyse accidents, by producing an Accimap to show how a particular event occurred by considering the whole system and to suggest system recommendations to mitigate these risks in future (Debrincat et al., 2013; Kant and Khobragade, 2022; McIlroy et al., 2021; Parnell et al., 2017; Stanton et al., 2019; Underwood and Waterson, 2014). Part of the Accimap approach is to create an actor map to show the different organisations, actors and decision-makers involved in the events leading to the accident at the position of those actors on the RMF (Svedung and Rasmussen, 2002). Actor maps have previously been used in the maritime domain to investigate maritime pilot's

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decision-making (Butler et al., 2022), as well as in the road transportation domain to explore global road safety (McIlroy et al., 2019) and the UK's automated driving system (Banks et al., 2019; Parnell et al., 2017) and to explore the resilience of New Zealand's freight transport system in the event of natural disaster (Ivory and Trotter, 2017). The actor map of New Zealand's maritime pilotage system was used to explore the different factors that affect maritime pilots' decision-making and the system level of each of those factors (Butler et al., 2022). Applying the RMF to the UK road transport system showed system weaknesses at the different system levels (Banks et al., 2019). The actor map of New Zealand's freight transport system identified governance opportunities to support the resilience of the networks such as creating a lessons-learned mechanism within the system and investigating actors with less visible roles, the local authorities to understand how they can be supported (Ivory and Trotter, 2017).

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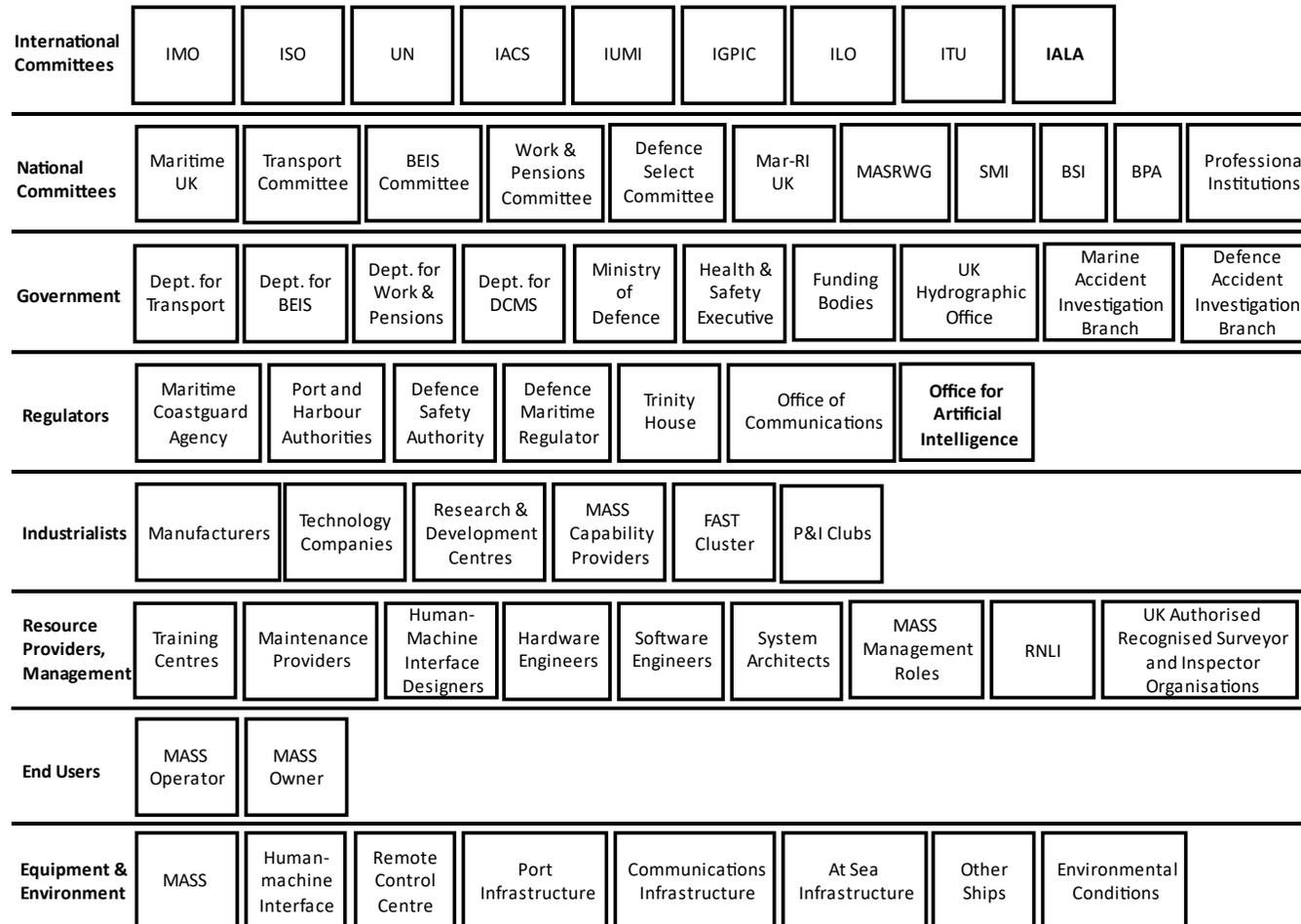


Figure 8.3 - Actor map for the UK MASS system. (Note: actors included only in the future MASS system are highlighted in bold. International Maritime Organisation (IMO), International Standards Organisation (ISO), United Nations (UN), International Association of Classification Societies (IACS), International Union of Marine Insurance (IUMI), International Group of Protection and Indemnity Clubs (IGPIC), International Labour Organisation (ILO), International Telecommunication Union, International Association of marine aids to navigation and Lighthouse Authorities (IALA), Business, Energy and

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Industrial Strategy (BEIS), Maritime Research and Innovation UK (Mar-RI UK), Maritime Autonomous Systems Regulatory Working Group (MASRWG), Society of Maritime Industries (SMI), British Standards Institution (BSI), British Ports Association (BPA), Digital, Culture, Media and Sport (DCMS) and Royal National Lifeboat Institution (RNLI.)

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To develop the actor map for the UK MASS system shown in Figure 8.3, relevant actors were identified using previous actor maps that have been developed (Banks et al., 2019; Parnell et al., 2017), government documentation (e.g., Department of Transport, 2021; Defence Maritime Regulator, 2020), UK government (gov.uk) and UK parliament websites (parliament.uk), relevant organisations' websites (e.g., IMO, International Association of Classification Societies and Society of Maritime Industries) and Maritime UK's code of practice (Maritime UK, 2020). Then to create the social network links were added between the actors in the actor map, a two-way link was added to and from the pair of actors if there was a two-way interaction between them, if the actors had been working with each other or they have responsibilities to each other. For example, a two-way link was added between the International Association of Classification Societies (IACS) and the International Standards Organisation (ISO) as they work cooperatively to develop international maritime standards. Another example of a two-way interaction was between the IMO and MCA as the MCA enforces IMO regulation in the UK but the MCA is also the UK's representative at the IMO. Alternatively, actors may have one-way interactions where one actor has a direct influence over another and there is no reciprocal relationship. Examples of one-way interactions within the social network are from Trinity House to Maritime UK, as Trinity House is a member of Maritime UK and from Maritime Research and Innovation UK to technology companies, as the committee is responsible for giving out the projects to the technology companies. Interactions were defined as direct communications between the two actors which could then influence the other actor, however these types of communications differed depending on the system level of each actor.

Maritime UK's code of practice (Maritime UK, 2020) was one document that was used to develop the UK actor map and social network, it contained a list of contributing organisations that are part of the MASRWG who developed the UK code of practice. The list of contributing organisations was then reviewed and the relevant organisations' websites, e.g., National Oceanography Centre (noc.ac.uk), Lloyds Register EMEA (lr.org) and Ocean Infinity (oceaninfinity.com) were then used to understand what level of the RMF the actor would be positioned on and the type of category they might come under, e.g., the National Oceanography was identified as a Research and Development Centre, Lloyds Register EMEA as a Classification Society and Ocean Infinity as a MASS Manufacturer. Similarly, other international committees (e.g., International Group of P&I Clubs) and national committees (e.g., Maritime Research and Innovation UK) also included member lists on their websites which identified more actors and the organisations that they are affiliated with, which were added as one or two-way connections depending on the relationship between the actors. UK government and parliament websites were used to understand the responsibilities of the

government departments (e.g., the Department of Transport and the Department of Business, Energy and Industrial Strategy) and agencies (e.g., the Maritime Coastguard Agency) to determine whether they were an actor within the UK MASS system and if there was any relationship with other public bodies. Government documentation such as the Department of Transport's Future of transport regulatory review consultation on Maritime autonomy and remote operations was used to understand the current regulations for MASS within the UK (Department of Transport, 2021). The Defence Maritime Regulations were also used to understand the current military regulations for MASS (Defence Maritime Regulator, 2020). Actors within the industry, end users, resource providers, management and equipment and environment levels, were identified using other actor map examples (Banks et al., 2019; Parnell et al., 2017) and Maritime UK's Code of Practice (Maritime UK, 2020), one way and two way connections were then identified between these actors based on the role of each actor.

It went through a three-stage review process to refine the actors and connections between the actors of the current and future MASS systems with three Subject Matter Experts (SMEs) involved in the development and regulation of MASS. A three-stage review process was used as the three SMEs had more expertise in different aspects of the MASS system, so the combined experience of the SMEs meant that all the RMF system levels were covered. The actor map was then used to investigate the interconnections between the actors and formal links (regulations specifically for MASS) within the current MASS system. The first SME consulted was an Associate Professor with 19 years of experience within the maritime domain and six years working with MASS including operational experience in the development of MASS, therefore they had industry experience, operational experience as an end user and knowledge of the resources providers and equipment and environment levels also. This discussion was used to add to the initial social network of the current MASS system that had been created using documentation and organisations' websites. Links were then added to the network to show where the system is currently being developed and to show what links could exist in a future MASS system if there were regulations put in place for MASS.

The current and future MASS social networks were then taken to the second SME, a System Architect with 25 years of experience within the maritime domain experience primarily in the Defence sector. The SME had expertise on the industry and resource providers level, especially in the military domain, so could add and modify connections between the military actors (e.g., the Defence Maritime Regulator and Defence Safety Authority) within the MASS system. After this review, one actor and 27 connections were added to the current MASS network and one link was removed from the network. The updated MASS networks were then taken to the third SME, an Autonomy

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Technical Specialist with 10 years of experience in the maritime domain and seven years working with MASS specifically, this SME had experience on the regulator, and government levels as well as knowledge of the national and international committee levels in the maritime domain, so had a comprehensive view of the higher system levels. The current MASS network was then edited adding 14 actors and 92 connections and removing six connections. The current MASS network was then edited adding 14 actors and 92 connections and removing six connections. Figure 8.4 shows an extract of the current MASS network showing just the MASS node's connections within the current network. The full current MASS network is not shown here due to its complexity but for the full current MASS network see Appendix G. Two actors were then added to the MASS future network and 12 connections were also added to the future network to give the final future network, the links added to create the future network are shown in Figure 8.4. For the full detailed version of the future network and the networks of each sub-level of the RMF see Appendix G.

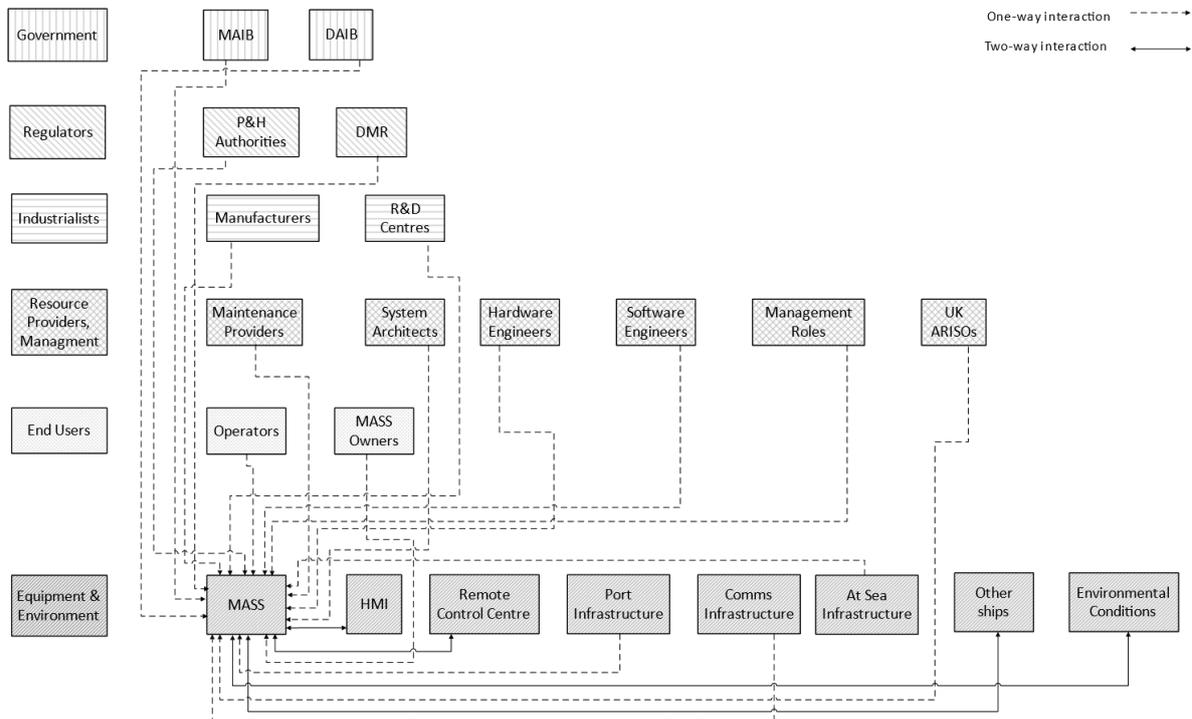


Figure 8.4 - Directed social network for the current UK MASS system (note: larger dashed lines reflect one-way interaction whereas solid lines reflect two-way interaction between agents. Marine Accident Investigation Branch (MAIB), Defence Maritime Regulator (DMR), Defence Accident Investigation Branch (DAIB), Research and Development Centres (R&D Centres, UK Authorised Recognised Inspection and Surveyor Organisations (UK ARISOs), Human-Machine Interface (HMI).)

### 8.3 Social Network Analysis

Social Network Analysis was then used to assess the current and future networks' dynamics. Analysing the UK MASS system as a social network shows which nodes have a high level of influence in the network (Banks et al., 2019). A node may have a high degree of influence due to the node's number of emissions and receptions to/from other nodes or due to its position in the network (Banks et al., 2019). Identifying the nodes that have a high degree of influence can show where greater redundancy is required in the system, it will also show the degree of influence of each of the RMF levels, showing where the system may need further support and allowing system recommendations to be made for each RMF level (Banks et al., 2019; Plant and Stanton, 2016c). The social network analysis will also show how the different levels of the RMF for the MASS system interact with each other (Banks et al., 2019). By comparing the current and future networks developed it will be possible to see the effects of introducing regulations and standards specifically for MASS and how this would affect each RMF level and the system's dynamics. The global and nodal metrics used for the analysis can be seen in Table 8.1 along with their definitions. These network metrics were chosen as they have been used to analyse networks in several other applications to identify key nodes within networks and assess network dynamics such as distributed flight crews (Stanton et al., 2016), driving automation (Banks and Stanton, 2016; Banks et al., 2019), digital nuclear power plant controls crews (Zhang et al., 2022), and submarine command teams (Stanton et al., 2017a). The global and nodal metrics were calculated using the Social Network Analysis tool AGNA (Benta, 2005) and the power centrality diagrams were produced using the Social Network Visualizer tool, SocNet V (Kalamaras, 2021). The results of the social network analysis for the current network and future network can be seen in Table 8.2 (global metrics) and Table 8.3 (nodal metrics).

Table 8.1 - Global and nodal metrics selected for analysis, along with their definition (Banks et al., 2019).

	<b>Metric</b>	<b>Definition</b>	<b>Maritime Context</b>
Global Metrics	Nodes	The total number of 'entities' or nodes within the network.	The total number of actors identified with the UK MASS system.
	Edges	Number of pairs of connected 'entities' or nodes	The total number of connections between the actors within the UK MASS system.
	Density	Represents the level of interconnectivity between (Kakimoto et al., 2006). Essentially represents a fraction of the total number of possible relations	The total number of connected actors/agents within the UK MASS system divided by the total possible

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(Stanton et al., 2017a). The following formula can be used:

$$\text{Network density} = \frac{2e}{n(n-1)}$$

where:

$e$  is the total number of links within the network

$n$  is the number of nodes within the network

number of connections (if all the actors were connected to each other).

**Diameter** The largest geodesic distance within the network (i.e., how many ‘hops’ it takes to get from one side of the network to the other) (Stanton, 2014). It is calculated using this following formula (Bin et al., 2018):

$$\text{Diameter} = \frac{\sum_i > j^{d_{ij}}}{n(n-1)/2}$$

where:

$n$  is the number of node pairs

$d_{ij}$  is the shortest path between node  $i$  and  $j$

The largest number of actors you would need to travel through to get from one side of the network to get to the other side, the network diameter is a measure of the distance between the actors within the MASS system.

**Cohesion** Presents the number of reciprocal links divided by all the possible connections (Stanton, 2014).

Refers to the number of two-way connections between the actors in the MASS network divided by the number of all possible connections. An example of a two-way connection is between the IMO and MCA, where the MCA is the UK representative to the IMO and the MCA enforces policies set out by the IMO.

### Nodal Metrics

**Emission** Total number of links emanating from a node within the network

For each actor this is the number of links from that actor to another.

**Reception** Total number of links received by a node within the network

The number of connections being received from other actors with the MASS system.

**Sociometric Status** A measure of ‘how busy’ a node is in comparison to all other nodes (Houghton et al., 2006). It is the number of emissions and receptions relative to the number of actors within the network and therefore provides an indication of node prominence within the network (Salmon et al., 2012b). It is

Sociometric status of the MASS system actors describes how connected that actor is to other actors within the system i.e, how many connections there are from that actor to other actors and how many

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calculated using the following formula outlined by Houghton et al. (2006):

$$\text{Sociometric Status} = \frac{1}{g-1} \sum_{j=1}^g (x_{ij}, x_{ji})$$

where:

$g$  is the total number of nodes in the network

$i$  and  $j$  are individual nodes

$x_{ij}$  are the number of communications between node  $i$  and node  $j$

$x_{ji}$  are the number of communications between node  $j$  and node  $i$

connections there to the actor from other actors.

### Centrality

Centrality is calculated to determine the most central or key nodes within the network (Stanton, 2014). There are a number of centrality metrics available in the literature, but we utilise the Bavelas-Leavitt (B-L) Centrality Index in this analysis. B-L centrality is the sum of all distances within the network divided by the sum of all distances to and from the node (Stanton et al., 2017a). It is calculated using the following formula outlined by Houghton et al. (2006):

$$\text{B-L Centrality} = \frac{\sum_{i=1; j=1}^g \delta_{ij}}{\sum_{j=1}^g (\delta_{ij} + \delta_{ji})}$$

where:

$g$  is the total number of nodes in the network

$\delta_{ji}$  is the geodesic distance between nodes

The centrality of the actors within the MASS system describes the position of the actor within the MASS system. The higher the actor's centrality the more central a position that actor has in the MASS system, which means that they have a greater influence on the other actors in the MASS system.

### Closeness Centrality

Indicates how close a node is to all other nodes within the network. Closeness is the inverse of farness. It is calculated using the following formula (Bavelas, 1950):

$$\text{Closeness} = \frac{n-1}{\sum_j d(i,j)}$$

where:

$n$  is the number of nodes within the network

$d(i, j)$  is the distance of the shortest path between nodes  $i$  and  $j$

Closeness centrality describes how close an actor is to all the other actors within the MASS system. An actor in the MASS system with a high closeness centrality could have a high degree of influence within the network due to their close position with many other actors in the system.

### Farness Centrality

Sum of the distances of the shortest paths from the node to every other node in the network (Stanton et al., 2017a).

Farness centrality describes the distance from the actor to all the other actors within the MASS network. An actor with a high farness centrality would have a low degree of

Betweenness Centrality	<p>The presence of an actor between two other actors (Stanton, 2014). It is calculated using the following formula, as outlined by (Freeman, 1977):</p> $\text{Betweenness} = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$ <p>where:  <math>V</math> represents the node  <math>\varepsilon</math> represents the edges or links between nodes  <math>\sigma_{st}</math> is the total number of shortest paths from node <math>s</math> to <math>t</math>  <math>\sigma_{st}(v)</math> is the number of those paths that pass through <math>v</math></p>	<p>influence over the MASS system due to their distance from the other actors within the network.</p> <p>Betweenness Centrality describes how many times an actor is between other actors in the MASS network. An actor with a high betweenness value means they have a high degree of influence on the actors they are in between.</p>
Power Centrality	<p>Power Centrality is a generalised degree centrality that takes into account the number of connections of a node's neighbours and their weightings. It is calculated using the following formula (Gil and Schmidt, 1996; Sinclair, 2009), for graph <math>G = (V, E)</math>, let <math>R(v, G)</math> be the set of vertices reachable by <math>v</math> in <math>V/v</math>,</p> $\text{Power Centrality} = \frac{\sum_{i \in R(v, G)} \frac{1}{d(v, i)}}{ R(v, G) }$ <p>where:  <math>d(v, i)</math> is the geodesic distance from <math>v</math> to <math>i</math> in <math>G</math>  The index is taken to be 0 for isolates, the measure takes a value of one when <math>v</math> is adjacent to all reachable nodes, and approaches 0 as the distance from <math>v</math> to each node approaches infinity. For finite <math>N =  V </math>, the minimum value is 0 if <math>v</math> is an isolate, and otherwise <math>1/(N - 1)</math>.</p>	<p>An actor within the MASS system that has a high power centrality, has a high degree of influence within the MASS system due to its position relative to the other actors within the system.</p>

### 8.3.1 Current MASS Network

Table 8.2 shows the results of the global metrics for the current network (see Appendix F for the complete network) showing that there were 60 nodes found in the network and 298 edges (pairings of connected nodes). The network analysis for the future system is detailed in section 8.3.2. The global metrics for the current network showed that the system is loosely coupled (i.e. the actors within the system act independently of each other) due to its low density (0.084) and cohesion

values (0.053) (Plant and Stanton, 2016c). The network density describes the comparison between the number of possible interconnections and the number of actual interconnections in the network (see Social Network Analysis was then used to assess the current and future networks' dynamics. Analysing the UK MASS system as a social network shows which nodes have a high level of influence in the network (Banks et al., 2019). A node may have a high degree of influence due to the node's number of emissions and receptions to/from other nodes or due to its position in the network (Banks et al., 2019). Identifying the nodes that have a high degree of influence can show where greater redundancy is required in the system, it will also show the degree of influence of each of the RMF levels, showing where the system may need further support and allowing system recommendations to be made for each RMF level (Banks et al., 2019; Plant and Stanton, 2016c). The social network analysis will also show how the different levels of the RMF for the MASS system interact with each other (Banks et al., 2019). By comparing the current and future networks developed it will be possible to see the effects of introducing regulations and standards specifically for MASS and how this would affect each RMF level and the system's dynamics. The global and nodal metrics used for the analysis can be seen in Table 8.1 along with their definitions. These network metrics were chosen as they have been used to analyse networks in several other applications to identify key nodes within networks and assess network dynamics such as distributed flight crews (Stanton et al., 2016), driving automation (Banks and Stanton, 2016; Banks et al., 2019), digital nuclear power plant controls crews (Zhang et al., 2022), and submarine command teams (Stanton et al., 2017a). The global and nodal metrics were calculated using the Social Network Analysis tool AGNA (Benta, 2005) and the power centrality diagrams were produced using the Social Network Visualizer tool, SocNet V (Kalamaras, 2021). The results of the social network analysis for the current network and future network can be seen in Table 8.2 (global metrics) and Table 8.3 (nodal metrics).

Table 8.1), this network was found to have a low density as it is spread out with few links (Plant and Stanton, 2016c). It was also found that the cohesion of the network was low, showing that there are a low number of reciprocal links in the MASS network. As 60 nodes identified in the UK MASS network showed the high number of actors and decision-makers there are in the system showing its complexity, as there are many decision-makers that can influence the safety of operations.

Table 8.2 - Results of the global network metrics for the current and future MASS networks.

<b>Global Metric</b>	<b>Current Network</b>	<b>Future Network</b>
Nodes	60	62
Edges	298	352
Density	0.084	0.093
Diameter	8	8

Cohesion	0.053	0.054
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Table 8.3 shows a summary of the nodal analysis results for the current network (see appendix F for the full results). The nodal metrics show that the government and industry tiers both have a much higher number of emissions than the other tiers, with 61 and 60 emissions. The highest number of receptions were found in the equipment and environment tier (54) of the RMF, as many of the nodes in this level are dependent on the higher levels. The second-highest number of receptions was seen in the industry tier (53), the nodes within the industry tier were found to be highly connected within the tier and to the nodes within the resource provider's tier.

To assess the importance of nodes within a social network Houghton et al. (2006) defined a key agent as a node with a sociometric status as greater than or equal to the mean status plus one standard deviation (for this network,  $0.17 + 0.11 = 0.28$ ). This identified seven key agents for the current MASS network: manufacturers, research and development centres, technology companies, MASS, MASS operators, the MASRWG and the Department of Transport. The nodes with the highest sociometric statuses were research and development centres, manufacturers and technology companies which are all nodes from the industry level. The industry nodes are highly connected to the resource providers (e.g., system architects, HMI designers, maintenance providers and training centres), end-users and equipment and environment levels, to the other industry nodes, as well as being connected to various national committees. MASS had the next highest sociometric in the current network, as it is highly connected due to its direct dependency on the actors within the industry and resource provider's levels and its connections to other nodes within the equipment and environment level. The MASRWG was also identified as a key agent, it is a highly connected node as the group has developed the voluntary UK Code of Practice for MASS and the group consists of manufacturers, technology companies, classification societies, training centres, research and development centres, the Department of Transport, the MCA and the MoD. The MASS operators' node was found to be a key node due to its connections with the equipment and environment level and its dependency on the higher levels such as the industry and resource providers levels. Lastly, the Department of Transport was found to be a key agent, which has connections to national committees (e.g., Transport Select Committee and British Ports Association), government bodies (e.g., the UK Hydrographic Office and Marine Accident Investigation Branch) and regulators such as the MCA and Trinity House.

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The sociometric status of a node compares how busy a node is in comparison to the other nodes in the network, in contrast, centrality measures the position of a node and how central it is within the network rather than measuring how many connections it has (Houghton et al., 2006). Therefore, a node may have a high sociometric status but may not have a high level of centrality within the network. Houghton et al. (2006) also suggested that key agents in a social network could be identified using centrality, agents with a centrality higher than or equal to the mean plus a standard deviation (i.e.,  $30.87 + 5.09 = 35.96$ ) can also be identified as key agents due to their central position within the network. Using centrality identifies eleven key agents in the current MASS network: research and development centres, the MCA, manufacturers, funding bodies, technology companies, the MASRWG, the Department of Transport, the UK Hydrographic Office, MASS operators, the Society of Maritime Industries and the MoD. Similarly, to sociometric status the centrality results show that the industry level has a high degree of influence within the system as research and development centres, manufacturers and technology companies were all identified as key agents and the research and development centre node had the highest centrality. The MCA was identified as having the next highest centrality after the industry nodes, although it was found to have a low

sociometric status. Funding bodies, the UK Hydrographic Office, the MoD and the Society of Maritime Industries were all identified as key agents using centrality even though the nodes had low sociometric statuses. Key agents were also found within the government and national committee tiers, with the Department of Transport and the MASRWG having high centrality. MASS operators were also found to have high centrality within the MASS network, as well as having a high sociometric status.

The other centrality metrics (closeness, farness and betweenness) also showed similar findings with research and development centres, the Department of Transport, manufacturers, the MCA, the MoD and funding bodies having the highest values of closeness and the lowest values of farness. The nodes with the highest values of betweenness were research and development centres, funding bodies, MASS operators and the MCA, which were all identified as key agents using centrality. Similarly, the power centrality results shown in Figure 8.5, show that the industry nodes, research and development centres, manufacturers and technology companies have a high degree of influence due to their positions within the network.

The results of the social network analysis of the current network showed that the industry level had the highest levels of influence within the system. The results also showed whilst there are key agents within the national committee tier (the MASRWG and the Society of Maritime Industries) the top-down influence did not reach the regulator tier with only the MCA being identified as a key agent using centrality. To strengthen the MASS system, it will be important the standards and regulations are developed specifically for MASS. To give both the civilian and military regulators a higher degree of influence within the system to ensure that MASS are appropriately regulated and that the lower tiers such as industry and resource providers have the necessary guidance. The results also suggest that greater redundancy is needed in the system, as the MASS operator node was identified as a key agent using both centrality and sociometric, suggesting that there needs to be more support for operators from the other system levels.

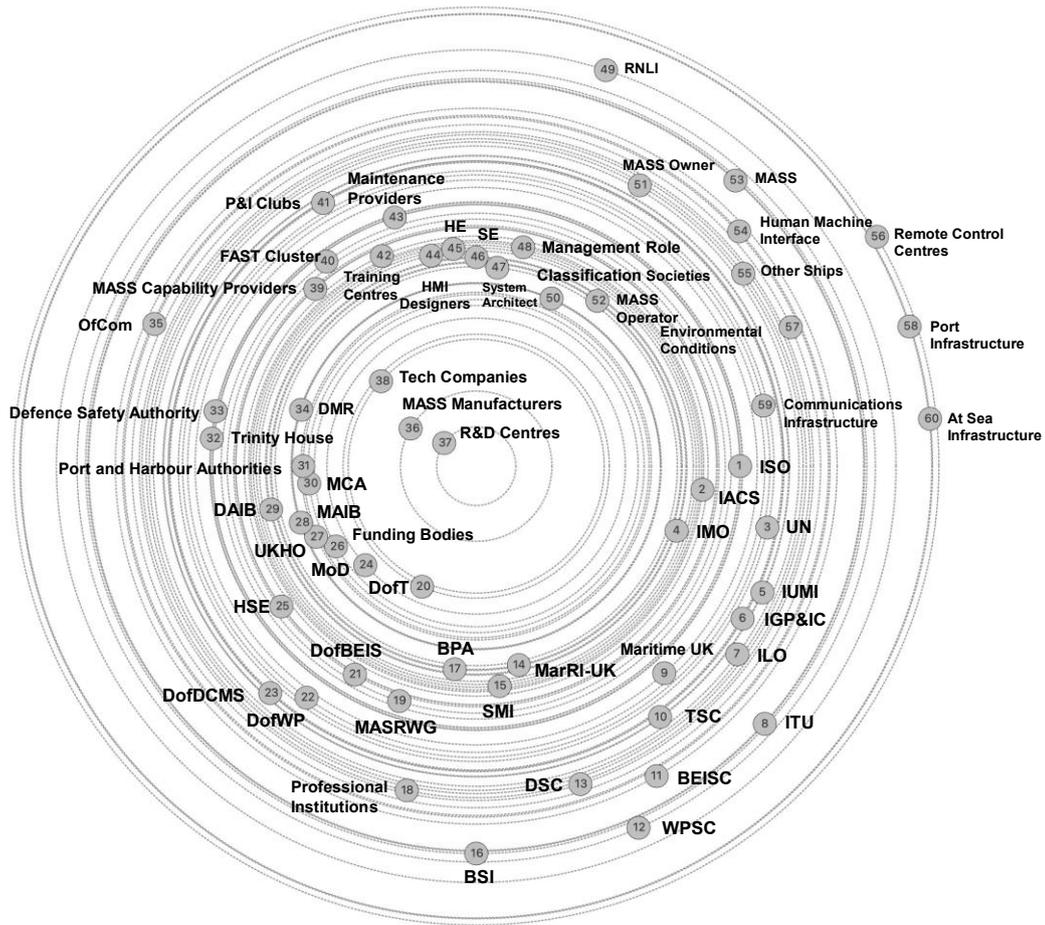


Figure 8.5 - Power Centrality plot for the current MASS network. (Note: for abbreviations list see Table G.1 in appendix G)

### 8.3.2 Future MASS Network

The MASS system will keep being updated as new technologies, regulations and standards are developed. This future MASS network has been developed as a starting point for discussion of what the future MASS system in the UK may look like. To create the future MASS network (see Appendix F.1 for the full future network) only two nodes were added to the current network the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and the Office for Artificial Intelligence. Also, 54 links were added (shown in Figure 8.6), mainly from the civilian and military regulators the MCA and the Defence Maritime Regulator to the industry, resource providers and equipment and environment levels. Further links were added from Professional Institutions (e.g., the Institute of Marine Engineering, Science and Technology and CEbotiX) to training centres, and then from training centres to MASS management roles and MASS operators to show the effects of the development of training courses and standards specifically for MASS. Table 8.2 shows the

results of the global metrics for the network showing that there are 62 nodes in the network and 352 edges, which is 54 more edges and two more nodes than the current MASS network giving the future MASS network a higher density (0.093) even though two more nodes were added to the network. The cohesion of the network also increased slightly to 0.054 due to the added reciprocal links within the future MASS network.

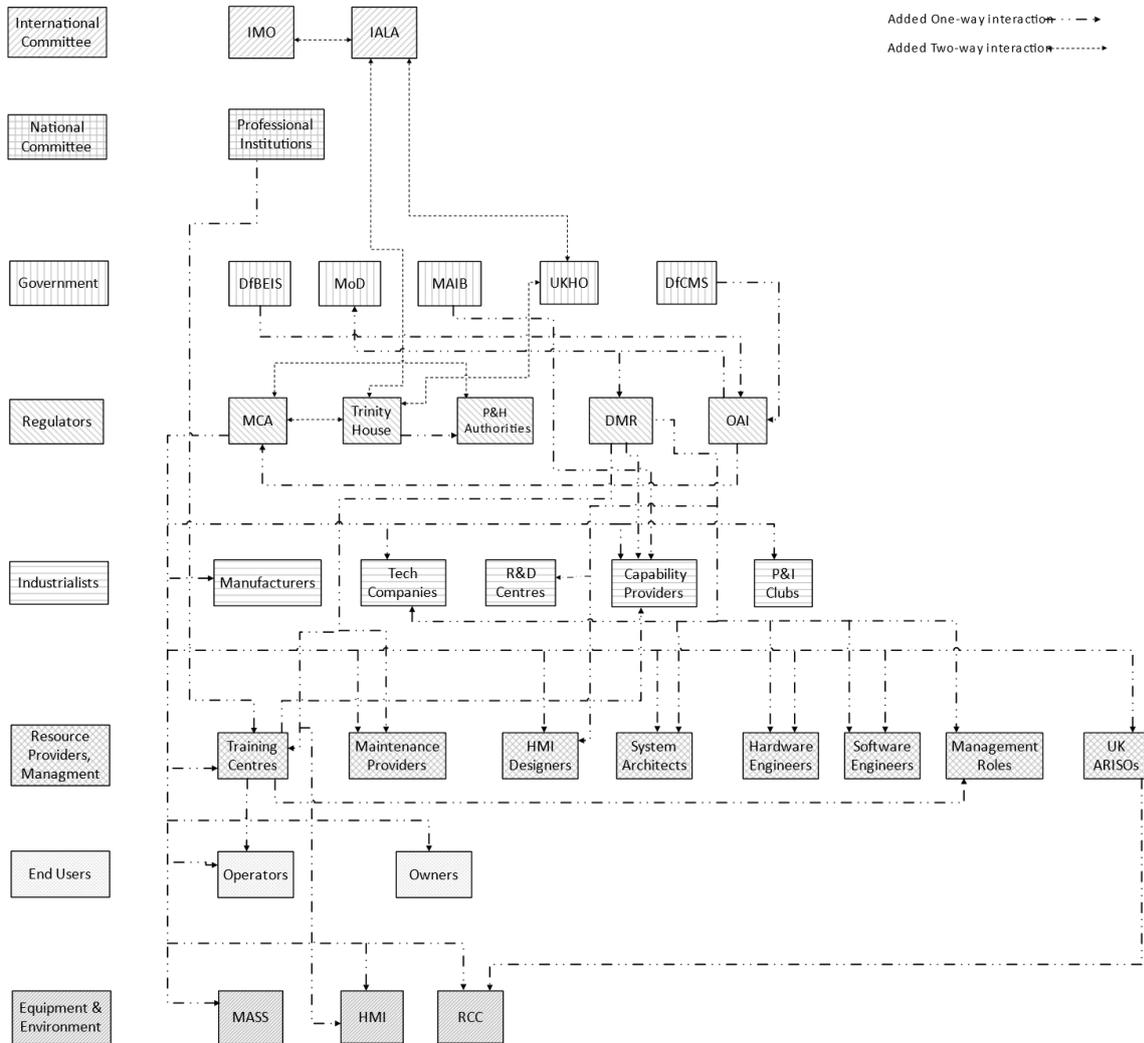


Figure 8.6- Directed social network showing the links added to create the future MASS network (note: dashed lines with dots reflect one-way interactions which have been added to create the future network and smaller dashed lines reflect two-way interactions that have been added. International Maritime Organisation (IMO), International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), Department of Business, Energy and Industrial Strategy (DofBEIS), Ministry of Defence (MoD) UK Hydrographic Office (UKHO), Department for Culture, Media and Sport (DfCMS), Maritime Coastguard Agency (MCA), Marine Accident Investigation Branch (MAIB), Port and Harbour Authorities (P&H Authorities), Office for Artificial Intelligence (OAI),

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Research and Development Centres (R&D Centres), Protection and Indemnity Clubs (P&I Clubs), UK Authorised Recognised Inspection and Surveyor Organisations (UK ARISOs), Human-Machine Interface (HMI), Remote Control Centre (RCC).)

A summary of the nodal metric analysis results for the future network are shown in Table 8.3 (see Table F.2 for the full results). In contrast to the current MASS network, where the largest number of emissions were found in the government and industry tiers, the regulator tier then had the highest number of emissions (69) within the network, followed by the government tier (66). In the future network, the tiers with the highest number of receptions were the industry tier (63) and the equipment and environment tier (60) which was similar to the receptions found in the current network.

The mean sociometric status plus a standard deviation was used to identify key agents within the future MASS network (i.e.,  $0.19 + 0.13 = 0.32$ ). This identified seven key agents within the future MASS network: the MCA, manufacturers, research and development centres, technology companies, MASS, the Defence Maritime Regulator and MASS operators. The main changes to the key agents from the current network were the addition of the two regulators, the MCA and DMR and both the MASRWG and the Department of Transport no longer being identified as key agents using sociometric status. The additional links from the MCA in the future MASS network increased the sociometric status from 0.25 in the current network to 0.66 in the future network making it the node with the highest sociometric status. The nodes with the next highest sociometric statuses were manufacturers, research and development centres and technology companies, whose sociometric statuses had increased slightly as the number of receptions for these nodes increased due to the added links mainly from the regulator level. The MASS node was also found to have the highest sociometric status, which increased slightly in the future network. The DMR was also found to be a key node within the future network, as like the MCA links were added from the DMR node to industry, resource providers and the equipment and environment nodes as if these current regulations for MASS had been introduced in the future network. Lastly, the MASS operator node was also still identified as a key agent.

The centrality results identified eight key agents within the network: the MCA, research and development centres, manufacturers, the MASRWG, technology companies, the Department of Transport, the UK Hydrographic Office, and MASS operators. Similar to those found in the current except for the Society of Maritime Industries, the MoD and funding bodies nodes are no longer identified as key agents.

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Table 8.3 – Summary of the nodal metrics results for the key nodes in the current and future MASS networks. (Note: asterisks denote key nodes in the network)

Hierarchical Level	Node	Node Metrics													
		Emission		Reception		Sociometric Status		B-L Centrality		Closeness		Farness		Betweenness	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
International Committee	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
National Committee	Society of Maritime Industries	6	6	8	8	0.24	0.23	36.48*	35.82	0.36	0.36	165	170	234.19	211.55
	Maritime Autonomous Systems Regulatory Working Group	4	4	15	15	0.32*	0.31	38.19*	39.90*	0.35	0.39	168	157	251.39	228.98
Government	Department of Transport	10	10	9	9	0.32*	0.31	38.06*	39.09*	0.43*	0.46*	138	133	441.90*	334.54*
	Ministry of Defence	9	9	6	7	0.25	0.26	36.02*	36.96	0.41*	0.44*	143	139	456.14*	418.19*
	Funding Bodies	7	7	6	6	0.22	0.21	39.11*	38.70	0.41*	0.41*	144	148	605.90*	499.57*
	UK Hydrographic Office	6	8	5	7	0.19	0.25	37.94*	38.57*	0.40*	0.42*	147	146	90.66	129.67
Regulators	Maritime Coastguard Agency	7	28	8	12	0.25	0.66*	39.93*	46.28*	0.41*	0.54*	143	112	520.78*	1007.83*
	Defence Maritime Regulator	7	17	3	4	0.17	0.34*	33.39	35.82	0.38*	0.44*	154	140	71.96	87.44
Resource Providers, Management	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industry	MASS Manufacturers	18	18	15	16	0.56*	0.56*	39.51*	40.31*	0.42*	0.42*	142	145	337.33*	253.15

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	Research and Development Centres	18	18	12	14	0.51*	0.52*	43.09*	45.20*	0.47*	0.48*	125	126	868.24*	814.04*
	Technology Companies	13	13	12	14	0.42*	0.44*	38.32*	39.22*	0.40*	0.40	149	154	316.05	268.38
End User	MASS Operators	8	8	11	13	0.32*	0.34*	37.20*	37.93*	0.35	0.35	168	172	544.61*	476.02*
Equipment and Environment	MASS	4	4	21	22	0.42*	0.43*	28.91	28.57	0.21	0.21	276*	284*	268.21	258.69
	<b>Mean Score</b>	<b>4.97</b>	<b>5.68</b>	<b>4.97</b>	<b>5.68</b>	<b>0.17</b>	<b>0.19</b>	<b>30.87</b>	<b>31.97</b>	<b>0.32</b>	<b>0.34</b>	<b>190.32</b>	<b>186.61</b>	<b>131.32</b>	<b>125.61</b>
	<b>Standard Deviation</b>	<b>3.51</b>	<b>4.78</b>	<b>4.05</b>	<b>4.48</b>	<b>0.11</b>	<b>0.13</b>	<b>5.09</b>	<b>5.50</b>	<b>0.06</b>	<b>0.07</b>	<b>45.48</b>	<b>47.65</b>	<b>179.28</b>	<b>192.02</b>



The MCA also had the highest centrality result as well as the highest sociometric status, showing that if there were regulations specifically for MASS it would lead to the MCA having a much higher degree of influence within the MASS system. The closeness and farness metrics also showed similar findings with the MCA, research and development centres, the Department of Transport having the highest values of closeness and the lowest values of farness.

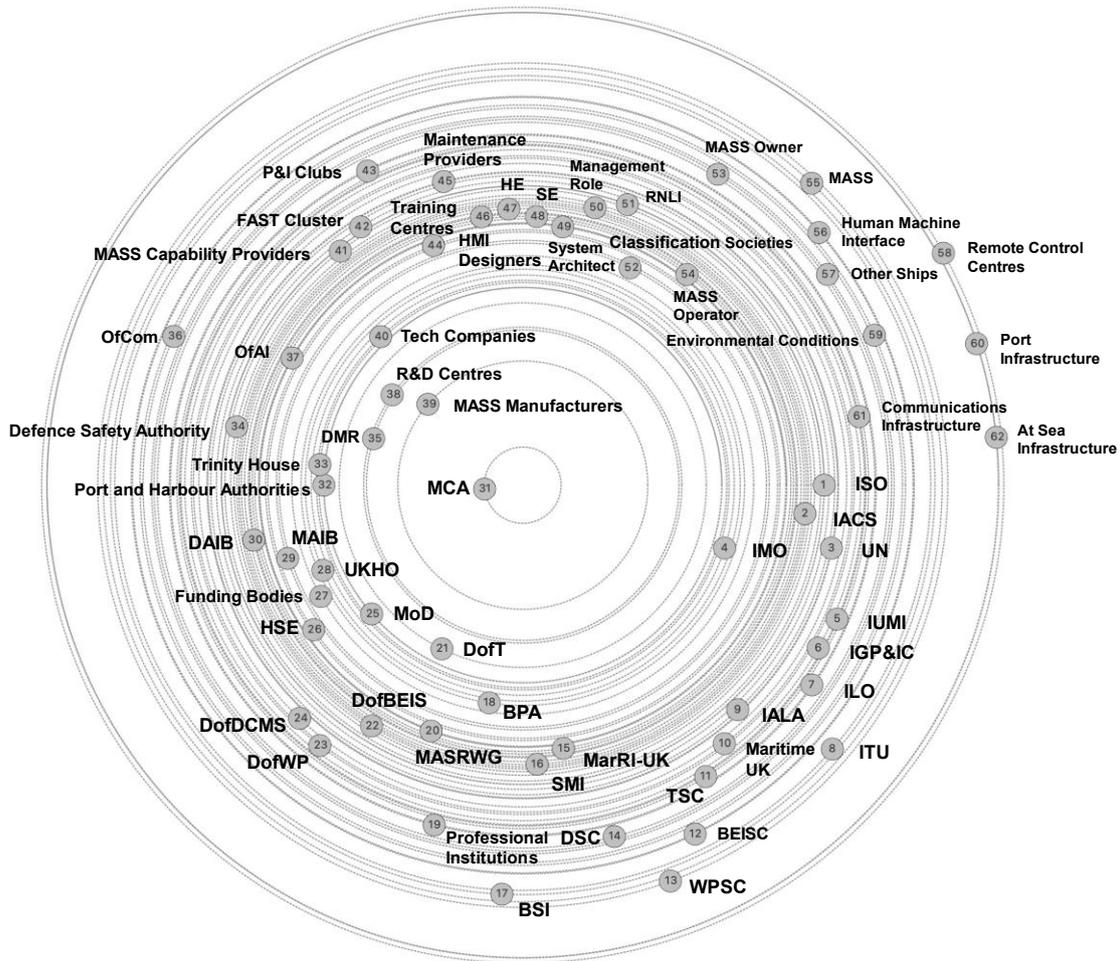


Figure 8.7 - Power Centrality plot for the future MASS network. (Note: for abbreviations list see Table C.1 in Appendix G)

Figure 8.7 shows the power centrality results in the future network, showing that the changes to the network have resulted in the MCA having the highest power centrality and therefore a greater influence within the network and the DMR power centrality also increased. In the future network the MCA, research and development centres, the IMO, funding bodies and MASS operators were found to have high values of betweenness. This was similar to the current network, although the MCA node then had the highest betweenness value which was much higher than the other nodes. Also, the IMO's betweenness centrality was found to be higher in the future network, although it was not identified as a key node in either the current or future network. The MASS operators' node had a decrease in betweenness in the future network but still had one of the highest values. The future MASS network

results show that the addition of formal regulations to the MASS network gives the regulators a higher influence within the MASS system, however, the industry nodes and the MASS operator still also have high degrees of influence within the system.

## 8.4 Discussion

System recommendations have been made for each level of the UK MASS system based on the social network analysis findings and are shown in Table 8.4, to suggest ways that each level could improve the overall system's safety. The analysis of the UK MASS system has shown that there are many decision-makers within the UK MASS system with 60 actors being identified in the Actor Map for the current MASS system. It has shown how the different RMF levels are involved in the overall safety of the system and therefore how different decision-makers within the system levels can influence safety. Similarly, the application of the RMF to maritime pilotage showed how different factors across the RMF system levels influence how maritime pilots make decisions, showing the applicability of the RMF in the maritime domain (Butler et al., 2022). It also showed the complexity of operations in the maritime domain due to the wide range of factors identified and the actor map generated here also shows the complexity of the maritime domain, as 60 actors were identified across all the RMF levels for the current system and the number of actors will increase as the system develops further (Butler et al., 2022).

Other applications of the RMF in the maritime domain also support these findings, Lee et al. (2017) and Kee et al. (2017) analyses of the Sewol Ferry accident highlighted how shortfalls in the legislator and regulator levels can influence the rest of the system levels below leading to an accident. These applications of the RMF highlight that it is important to look beyond the more obvious decision-makers within a sociotechnical system, e.g., the operators and those working within an RCC and consider how others in the higher-level system levels (e.g., regulators and government bodies) decisions will affect the overall safety of the system. The global metrics for the MASS system show how it is loosely coupled as it has a low network density and cohesion, however similar findings were also found when analysing the automated driving system (Banks et al., 2019). These findings further demonstrate the safety challenges in large and complex sociotechnical systems such as maritime and road where there are many actors involved, as many of the actors within the system do not directly communicate and are influenced or connected to other actors within the system. However, further work should investigate the connectedness of other domains such as aviation and understand what lessons may be learnt.

Although MASS are expected to bring safety benefits by removing onboard operators and therefore the risk to the life of the crew, the differences in how they will be operated due to their remote operation will mean that the operators will have to be more reliant on their automated systems to

operate the ship making the human-machine interaction more critical than it might be on a conventional vessel (Man et al., 2018b). One important issue will be providing operators and other personnel within an RCC with the necessary information to safely operate and navigate the MASS even though they will no longer have all of the same sensory feedback as they would onboard (Mallam et al., 2020; Man et al., 2016). This lack of 'ship sense' will affect their ability to maintain their SA and respond to situations appropriately (Man et al., 2016). The use of user-centred design approaches will be necessary to support operators when they are in a predominately monitoring role to keep operators engaged in their tasks so that the MASS' automated systems are being supervised (Man et al., 2018b). Industrialists, resource providers and end users will need further guidance on how to design and develop their MASS systems to minimise the risks of these human-machine interaction issues leading to incidents and accidents.

The application of the RMF and Social Network Analysis to the UK MASS system has shown the importance of actors within the international committees, national committees and regulators levels to system safety. Similar to Banks et al.'s (2019) findings for the automated driving system in the UK, in the current MASS system nodes in the industrialist's tier of the RMF were found to have high sociometric statuses and centrality within the network. There was also a lack of influence from the nodes within the regulator tier in both the automated driving system and the current MASS system (Banks et al., 2019). However, the MASRWG and Society of Maritime Industries were found to be key agents in the national committee's tier in the MASS system, whereas none was found in the automated driving system (Banks et al., 2019). This suggests there is a need for a greater top-down influence from the international and national committee levels to inform the new regulations and standards that are required to increase safety within the system. Although there is currently a lack of formal regulation from the regulators, national committees such as the MASRWG are working on developing the regulatory framework for the UK. Banks et al. (2019) recommended that a combined top-down and bottom-up sociotechnical approach should be taken, to ensure that innovation is not inhibited, and appropriate regulations and policies are in place to enable their safe operation, which suggests a similar approach may apply to the UK MASS system (Banks et al., 2019).

Kim and Schröder-Hinrichs (2021) highlighted the need for the MASS regulatory framework to be developed with proactive measures to reduce the gap between the regulatory framework and the technological developments, whilst ensuring that the framework does not inhibit innovation. The findings have shown that there is a high degree of influence from industry within the MASS system, which suggests that a proactive approach may need to be taken to reduce this gap (Kim and Schröder-Hinrichs, 2021). The development of regulations specifically for MASS will be necessary to ensure that they can interact safely with crewed ships (Hoem et al., 2021). This will be particularly important for preventing collisions between crewed ships and MASS as the International Regulations for Preventing Collisions at Sea (COLREG) 1972 rely on the judgement of the onboard seafarer (Jo et

al., 2020a). For example, COLREG Rule 5 states, 'Every vessel shall at all times maintain a proper lookout by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision', guidance will be needed on how should be achieved when the master is no longer onboard the vessel and they are operating a MASS from an RCC. In addition to standards for interacting with conventional vessels, MASS will also need to be able to interact with other MASS safely so further amendments may be required to include these new aspects (Hannaford and Hassel, 2021).

Due to the differences in how crewed and uncrewed ships are operated, there are many gaps in the current standards and regulations which need clarification for remote operators such as definitions for "master", "crew" and "responsible person" and regulations referencing being onboard the vessel (Shiokari, 2020; Yoshida et al., 2020). The future MASS system developed showed that the MASS operator node was a key agent within the network as it had a high sociometric status and centrality. Therefore, it will be important that the roles and responsibilities of the operator and other roles involved in their operation are clearly outlined for the different levels of MASS automation (Kim and Schröder-Hinrichs, 2021; Man et al., 2015; Saha, 2021). It has been suggested that these roles and responsibilities could be defined using an operational envelope (Hoem et al., 2021). The operational envelope could be defined by the relevant operational constraints such as weather conditions, traffic and geographic complexity (Hoem et al., 2021).

Whilst there is a lack of formal regulations the MASRWG code of practice will be an important part of the MASS system as it develops and will need to be updated along with technological developments, especially as formal regulations from the IMO are not expected before 2028 (Department of Transport, 2021). However, there are gaps in the code of practice developed by MASRWG, as there is currently no guidance from the higher levels of the system some of the standards can only refer to crewed ships. For example, it is suggested that operators should have appropriate certification for a similar manned vessel. However, it has been highlighted by Deling et al. (2020) that there are many aspects of knowledge and skills that remote operators will need that are not currently included in seafarer training under the International Convention on Standards of Training, Certification and Watchkeeping 1978, such as gaps in automation knowledge, lack of training on diagnosing automated system faults and the aspects relating to remote control. It has been suggested that operators will need an overall understanding of the vessel and the RCC and how these parts of the system work together (Saha, 2021). The development of appropriate training courses for MASS operators will be important, to ensure that operators develop the necessary skills to operate MASS safely, as their operation will differ from that of a conventional crewed ship.

It has also been identified that operators require training for intervening in emergencies and it was suggested that simulators and virtual reality could be used to give operators experience in these

scenarios (Saha, 2021; Yoshida et al., 2020). Kim and Mallam (2020) Delphi study of the International Convention on Standards of Training, Certification and Watchkeeping (STCW) 1978 leadership competencies and it was suggested that new knowledge, understanding and proficiency (KUP) for leadership will also be required for operators at RCCs. One new KUP that was suggested was, the knowledge and ability to acquire, handle and comprehend large amounts of system information, as when the operators are working at an RCC they will potentially be receiving large volumes of sensor data and there will be fewer personnel in the RCC versus on a manned bridge. Therefore, how an operator will need to comprehend and interpret different system information to inform their decision-making might change (Kim and Mallam, 2020). This shows that not only will the technical regulations and standards developed for the ships be important, but the regulations and standards for RCC personnel will also be important as these will affect how the operators and other roles such as the master and chief officers and chief engineers are trained. It has been highlighted that the experience and training of the remote MASS operators will be critical to the safe navigation of ships (Deling et al., 2020; Yoshida et al., 2020). Various professional institutions such as MASSPeople and CEbotiX are already investigating training requirements for operators of MASS and developing training standards for operators (Furgo, 2021; National Oceanography Centre Innovations Ltd, 2021). The development of these training courses for MASS operation will then lead to the added links from training centres in the future MASS system network, which will help to improve the system's resilience.

Table 8.4 – MASS System recommendations for each hierarchical level in the RMF.

Hierarchical Level	Findings	Recommendations
International Committees, National Committees, Government	<ul style="list-style-type: none"> <li>The comparison of the current and future MASS system analysis showed a lack of influence from the regulators due to the absence of regulations from higher levels.</li> <li>The analysis showed in both the current and future systems that the MASS operator had a high degree of influence within the system, due to its number of connections and position within the network.</li> </ul>	<ol style="list-style-type: none"> <li>Provide legislation for MASS specifically or alter current legislation to include definitions/clarifications for MASS where applicable.</li> <li>Clearly outline the roles and responsibilities of the master, and the operator for the different levels of automation.</li> </ol>
Regulators	<ul style="list-style-type: none"> <li>The results of the social network analysis showed that the industrialists have a high degree of influence with the current and future MASS system but did</li> </ul>	<ol style="list-style-type: none"> <li>Provide clear guidance to industrialists and resource providers on testing, maintenance, and certification for MASS.</li> </ol>

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	<p>not have connections to the regulators in the current network.</p> <ul style="list-style-type: none"> <li>The social network also showed there was a lack of connections between the regulators and resource providers including regulations for training centres for MASS operators.</li> </ul>	<p>4. Give guidance to resource providers and end-users on training qualifications that are required to operate a MASS at the different levels of automation.</p>
Industrialists	<ul style="list-style-type: none"> <li>MASS was defined as a key actor within the MASS system so it will be important that it undergoes sufficient testing before being operated.</li> <li>The MASS operator was also found to have a high degree of influence, so it will be important that they are sufficiently supported by using human centred design approaches and that they have appropriate guidance on the operational constraints of the MASS.</li> </ul>	<p>5. Ensure that the MASS has undergone sufficient testing and that potential risks during operation have been identified.</p> <p>6. Provide clear guidelines to end-users on the operational constraints of the MASS.</p> <p>7. Use user-centred design principles when designing the MASS' systems.</p>
Resource Providers	<ul style="list-style-type: none"> <li>The comparison of current and future social network results showed that in the current MASS system that training centres do not have a high degree of influence but that it can be improved by the addition of training courses and qualifications specifically for MASS.</li> </ul>	<p>8. Provide appropriate training courses for operators of MASS and other roles involved in operating MASS.</p>
End User	<ul style="list-style-type: none"> <li>The MASS operator was found to be both a highly connected and central actor within the network, so it will be important they understand their role and responsibilities during operation and the limitations and constraints of the MASS.</li> </ul>	<p>9. Operators will need to have a clear understanding of what their roles and responsibilities are during operation.</p> <p>10. Operators will also need to understand what the operating constraints and limitations of the MASS are.</p>
Equipment and Environment	<ul style="list-style-type: none"> <li>The social network results showed that the MASS node is highly connected within the network, so it will be necessary for MASS to be appropriately</li> </ul>	<p>11. Make sure that MASS are appropriately maintained in line with the guidance given by industrialists and regulators.</p>

	maintained as failures could affect many other actors within the network.	
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One limitation of this approach is the subjectivity of the development of the directed social networks of the UK MASS system, the SMEs selected may have influenced the actors identified and the links between them due to their own biases. However, these risks have been mitigated by consulting three SMEs when creating the UK MASS networks, whose combined experience in the maritime domain covered all the RMF system levels and the networks went under multiple reviews. The UK MASS system networks could be developed further in the future by being reviewed by other SMEs with different types of experience, as this might impact the actors and connections included. However, whilst the MASS system is still under development this provides an initial analysis of the UK MASS system, although it will continue to change whilst it develops, and more MASS become operational. There will be more changes when new regulations and standards are put in place nationally and internationally, as the IMO has still yet to put into place any regulations and standards specifically for MASS, but this is likely to be further in the future. It could be that the IMO or MCA for the UK could keep a 'living document' that could be updated as the system evolves.

Although the IMO was not found to be a key node within either MASS network, it will still be an important node as any international regulations developed for MASS will then be enforced by the UK's flag state representative the MCA. This suggests there are limitations in using this approach as the links within the networks are not weighted in terms of their importance. Therefore, the networks do not reflect the IMO's importance and the difference in importance between other nodes of the networks. However, as MASS is still in the early stage of development this approach provides a starting point for further discussions on how the MASS system might be supported during this process and it could also be applied to other new technology areas such as Uncrewed Aerial Vehicles (UAVs) and artificial intelligence. This suggests that in future applications the method may need to be extended to include a weighting scale for the links within the social network created to model the sociotechnical system. As this was the first application of the method to the MASS system it was beyond the scope of the current chapter but in future applications of the method, a weighting system could be developed for the links between the actors in the network, for example, higher weightings could be assigned to links that have come from legislation that may have been put in place by the MCA or the IMO. Also, in some cases, there may be a strong connection between a pair of actors, which could be given a higher weighting and if there is a weaker connection, where information is exchanged but there's not necessarily a direct influence of one actor over another the link could be given a lower weighting.

Other Human Factors methods could be used to analyse future sociotechnical systems such as the MASS system and could be applied to further the findings here such as Cognitive Work Analysis

(Vicente, 1999) which can be applied to future systems to provide a comprehensive system analysis. Although CWA could be used to identify recommendations for the MASS system, the analysis would not necessarily show the different stakeholders and decision-makers involved in the entire MASS system, which was an advantage of using the RMF to create an actor map and using Social Network Analysis to investigate the influence of each of those decision-makers. Methods such as System Theoretic Process Analysis (STPA) (Leveson, 2011) and Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) could be used to identify further recommendations for the MASS system, as they can also be used to proactively assess risk in new and developing systems, once there is greater knowledge on how uncrewed MASS will be operated from RCCs and the control structures that have been put in place for their operation. Another method that would provide a comprehensive system analysis would be the Event Analysis of the Systemic Teamwork Framework-Broken Links (EAST-BL) (Stanton and Harvey, 2017) method which could be used to identify the risks when there are communications failures between actors and tasks in a socio-technical system. This approach would also identify who the actors are within the MASS system, however, it may not be appropriate to apply it to the social networks developed due to the scale of networks and further field data would be required to understand which links might be broken when an accident or incident occurs. EAST-BL could be applied to a MASS case study or specific MASS use case to better understand the risks of communication failures, once there is more knowledge on the specifics of MASS operations. Applying EAST-BL to a MASS case study could overcome some of the weaknesses in the combined RMF and Social Network Analysis approach as the field data could be used to apply weightings to the social, tasks and information networks.

### **8.4.1 Further Work**

Further work will be required to investigate the UK MASS system as it develops whilst its regulatory framework is put into place and suggest what can be done to improve the system further. The developed UK MASS network shown has been created as a starting point for this discussion but will require updating as the system develops. The networks created could be validated using field data from operational MASS in the future when the technology is more established and to extend the method by creating a weighting system for the different links between the actors. Although the future UK MASS system showed improved resilience there will still be a need to further investigate ways of supporting industrialists and the end-user to create greater redundancy within the system. Further work could investigate how standards might be developed for the new aspects of operating MASS including the requirements for RCCs and their personnel including the standards for their training. Also, the effects of failures within the MASS system could be investigated to understand what effects this would have on the system and what could be done to mitigate those risks. The networks were done for the UK MASS system generally, the networks could be extended to include

the different regulations related to ship type, ship size (overall length and tonnage) and the area of operation (open ocean, pilotage or inland waters) to show how each aspect might affect the system. The actor map and social network method could also be applied in other flag states to explore the differences between the UK and other flag states.

### **8.5 Conclusions**

A sociotechnical systems approach has been applied to the MASS system in the UK, and it has shown that there are many different actors within the system and the system goes beyond just the MASS and the operator. Two social networks of the UK MASS system were developed, one to show the connections that exist in the current UK MASS system and a second to show a future MASS system showing the effects of development of MASS specific regulations and standards. Social Network Analysis was then used to analyse the dynamics of the current and future MASS networks. The results showed that there is a need for a greater top-down influence in the current system from the international, national, government and regulator levels of the RMF to promote the safe development and operation of MASS. Also, the results showed that greater redundancy is needed within the MASS system, so there is less reliance on the end user.

Recommendations have been given to improve the UK MASS system's safety by giving recommendations for each of level of the sociotechnical system. The future MASS system shown contained additional links between the civilian and military regulators (the MCA and the Defence Maritime Regulator) and lower levels of the network, which showed that the development of a formal regulatory framework improved the system's resilience by creating a greater top-down influence. The MASS system is continuously changing as the regulations and standards are still being developed for MASS, including the development of training standards and qualifications for operators. This chapter shows the need to consider all the levels of the MASS system to understand the top-down influences as well as the bottom-up influences in the system. The findings of this chapter have shown that it will be necessary that MASS systems are designed using user-centred principles and the focus of the next chapter is the development of a user-centred design framework based on the research programme. The design framework outlines how the mixed-method approach used in this thesis can be used to design future MASS systems. The next chapter demonstrates at which stage of the design process each method could be applied and shows how the approach can be used to develop novel user-centred designs.



# **Chapter 9 The development of a user-centred design framework for future uncrewed Maritime Autonomous Surface Ship Systems**

## **9.1 Introduction**

This chapter aims to develop a design framework that shows a process of how the Human Factors methods in this thesis can be combined to aid the design and development of novel systems. The UCD framework shows how the methods outlined in this thesis can be used in the design process of novel systems and it has been co-developed and refined with the industrial sponsor of this work. Whilst the design framework has been developed using uncrewed MASS systems, it could be applied to the design of other future systems. The design framework brings together the methods and findings from all the other chapters of this thesis to describe how each method could be used in the early stages of designing a future system, to show how the methods can all be used to design systems that will support an operator making decisions in a HMT. It shows a process of how UCD principles and recommendations can be generated at early design stages, even when the system and users do not yet exist. The framework could be used to assist design teams in getting Human Factors input into the design process earlier, as it could be used to help stakeholders understand the utility of applying Human Factors methods in early design stages, by showing them the types of outputs that can be achieved. In this chapter, the process used to create the design framework is outlined. First, an initial framework was created from the thesis chapters to provide a starting point for the design framework. Then, industry SMEs were interviewed about the practices, standards and information sources currently used to develop MASS systems, and the evaluation techniques used. The industry SMEs were asked to review the initial design framework and make suggestions on how it could be adapted; these frameworks were then combined to create the final design framework.

### **9.1.1 User-Centred Design**

The design framework developed in this chapter follows a UCD process, which is fundamental when designing and evaluating systems to ensure the design will meet the skills, knowledge and abilities of the end-users (Harris, 2007). The risks of not utilising UCD processes in the early stages of the design process are that it may be too late or more expensive to make the design changes at a later stage (Stanton et al., 2017b). One challenge is during initial design development gaining stakeholder engagement for the need for Human Factors input at early stages. This design framework could be shown to stakeholders to show how various Human Factors methods can be applied at these early

stages and the work here provides examples for the types of outputs that they can generate from such methods, showing the benefits to a novel system's design of using this approach. It has been suggested that such UCD approaches are important in reducing the safety risks in maritime and are particularly important when considering human interaction with automated systems (Hsieh et al., 2024).

Multiple UCD frameworks have been suggested in the maritime domain (Costa et al., 2017; Grech and Lutzhoft, 2016; Hsieh et al., 2024; Kataria et al., 2015; Porathe, 2016). Costa et al. (2017) summarised a user-centred process for redesigning a ship manoeuvring system display located on the bridge. The design process followed ISO 9241-210:2010. The first stage of the design framework was identifying the need for UCD, followed by a pre-design stage, planning the user-centred process, and understanding the user requirements and context of use (Costa et al., 2017). The third stage was producing design ideas to meet the user requirements and context of use, evaluating the design against the requirements and then conducting a final design evaluation (Costa et al., 2017). Vu and Lützhöft (2020b) similarly outlined a UCD framework using the stages outlined in ISO 9241-210:2010. The adoption of systemic UCD approaches within the maritime domain is not common and designs are often considered from a technical and economic point of view (Vu and Lützhöft, 2020b). A focus group with maritime stakeholders was conducted to discuss the challenges of implementing user-centred approaches. One challenge identified was the complexity and fragmented nature of the maritime industry and there is a need to provide designers with more design guidance and tools that can be used (Vu and Lützhöft, 2020b).

Other UCD frameworks have been suggested, Porathe (2016) and Grech and Lutzhoft (2016) also adapted the user-centred process outlined in ISO 9241-210:2010 for e-navigation systems. Workshops were conducted with maritime stakeholders to identify gaps in the user-centred framework produced using ISO 9241-210:2010 and extend it. The design framework consisted of five main stages: concept development (generating user and organisational requirements), planning and analysis (system concept), design (prototype), integration and testing (meeting system usability goals) and lastly operational (maintaining operational usability; Grech and Lutzhoft, 2016). The first four stages were based on ISO 9241-210:2010 but the workshop findings suggested adding the operational stage to incorporate end users' operational feedback so it could be considered in future designs (Grech and Lutzhoft, 2016). In the workshops it was discussed that as user-centred processes are not mandatory there is no pressure on system designers to use such processes and is often seen as more expensive and time consuming without the benefits of using such an approach being seen (Grech and Lutzhoft, 2016). Kataria et al. (2015) used a user-centred approach using accident analysis and semi-structured interviews to explore how onboard designs can be improved to fit the crew, to expand the view from considering one user to the whole crew.

Veitch et al. (2021) applied a user-centred process to MASS to design a user-centred RCC for autonomous navigation again using ISO 9241-210 design process stages. As part of the context of use stage, stakeholder workshops were conducted using SMEs as this type of operator does not yet exist (Veitch et al., 2021). To identify the future users' needs, similar users from other domains were consulted, including interviewing autonomous bus operators and air traffic controllers due to the similarities between how the vehicles are operated (Veitch et al., 2021). This demonstrates how using UCD processes can be challenging when designing novel systems, as the users and/or the system might not exist. Therefore, it is necessary to consider what methods can be applied when there is limited access to end users and systems in use in the real world and how the results of these methods can be used to develop the design.

### **9.1.2 User Centred-Design Framework Methods**

To create the UCD framework for developing novel systems the methods used in this thesis were put into different design stages to show where they apply. The following section is a short overview of the UCD methods applied in each thesis chapter, which are all included within the design framework.

#### **9.1.2.1 The Perceptual Cycle Model, the Schema World Action Research Method and the Trust-Schema World Action Research method**

One method that has been used hypothetically is the PCM, see section 3.2 for a full description of the decision-making model. SWARM and T-SWARM were developed using the PCM framework (for further details see sections 4.1.2 and 0), which can be used to interview with end users and/or SMEs in early design stages for a future system, to provide design principles that are user-centred. The PCM is a user-centred framework, as it shows how the operator makes decisions by interacting with the system. It has been used to explore accidents to understand how to improve system design in aviation and automated driving and highlighting the risks in human-machine interactions (Banks et al., 2018a; Plant and Stanton, 2012). SWARM and T-SWARM methods have already shown their utility in the aviation domain as they have been applied to generate design recommendations for future flight decks (Banks et al., 2021; Parnell et al., 2021b) and to generate design recommendations for UAV pilots' trust (Parnell et al., 2022). These methods follow UCD principles as they put the operator at the forefront of the design process to ensure that their needs are captured and reduce the potential safety risks when designing highly automated systems.

#### **9.1.2.2 Hierarchical Task Analysis and Systematic Human Error Reduction and Prediction Approach**

HTA and SHERPA are also user-centred by considering the tasks that the operator needs to perform in the system and investigating what errors could be made during those tasks and their impact on the

operation. The application of HTA and SHERPA shows how it can be used to focus on human-machine interaction and reduce the likelihood of design induced errors occurring (for further details of the methods see Chapter 6, section 0). Similarly, SHERPA has been applied previously to provide system-based design recommendations in similar future aviation systems (Parnell et al., 2021a) and in maritime pilotage operations (Ernstsen and Nazir, 2018).

### **9.1.2.3 Behavioural Markers System**

The BMS for HMTs has been developed here to show how a machine teamwork behaviour can be designed to help support decision-making within the HMT. The BMS is another user-centred approach as it shows how designs can be considered in terms of the teamwork interactions in the HMT, showing how the system design can aid the operator in displaying teamwork behaviour.

### **9.1.2.4 Risk Management Framework and Social Network Analysis**

The application of the RMF and Social Network Analysis (see Chapter 8, sections 0 and 8.3 for further details of the framework and Social Network Analysis) is another user-centred approach. It does not focus specifically on the end user but considers all the stakeholders within the system as this approach provides a systemic view of a sociotechnical system. The RMF and Social Network Analysis have also shown their utility when they were applied to the road domain (Banks et al., 2019; Parnell et al., 2017).

## 9.2 Method

### 9.2.1 Initial development of the design framework

An initial Human Factors design framework shown in

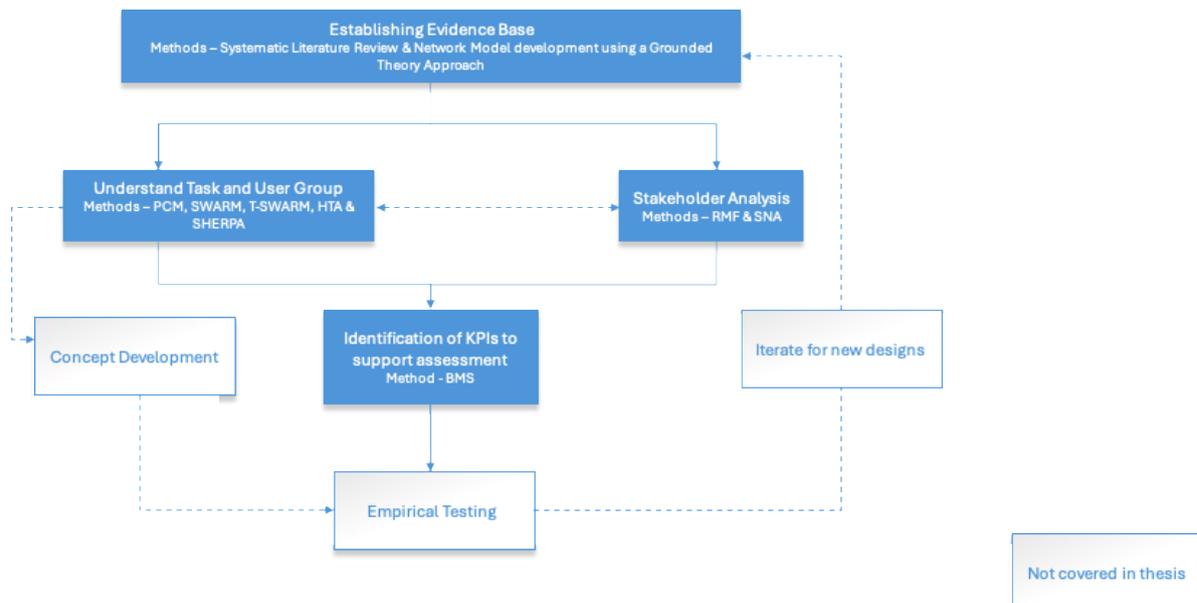


Figure 9.1 was developed from the chapters of this thesis to show a potential design process that could be used to design and develop future novel systems. The design framework only shows how process of developing initial prototype designs and does not cover the larger system design life cycle. The initial design framework consisted of six main steps, four of which were generated from Chapters 2 to 9 and two stages were added to complete the design process. First, the literature review in chapter two where the decision-making in HMT literature was investigated established an evidence base. The next two steps in the design framework could run in parallel; this was the stakeholder analysis and understand the task and user group. For the stakeholder analysis, Chapter 9 has shown how the RMF can be applied to look at the stakeholders across the system levels to understand what can be done to support all these system levels.

The majority of the thesis chapters have focused on how to understand the task and user group, which has shown that the PCM (Chapter 3), SWARM (Chapter 4), T-SWARM (Chapter 5), HTA and SHERPA (Chapter 6) are all applicable methods for generating design principles and mitigation strategies for the design and development of future MASS. After those steps, the identification of key performance indicators is required to support the evaluation of the design concept Chapter 8 has

shown the development of a BMS for MASS operations which could be used to evaluate the operator's performance and the abilities of the system to show teamwork behaviours.

Two final steps were then added that were beyond the scope of this thesis; the next step would be to develop a design concept which would be based on the outputs from the understand the task and user group and the stakeholder analysis steps. The final step would be empirical testing to test the concept design for the MASS system, which would use the key performance indicators identified in one of the previous steps and the results of this testing could then be used to iterate and feed into the design of the next generation of system.

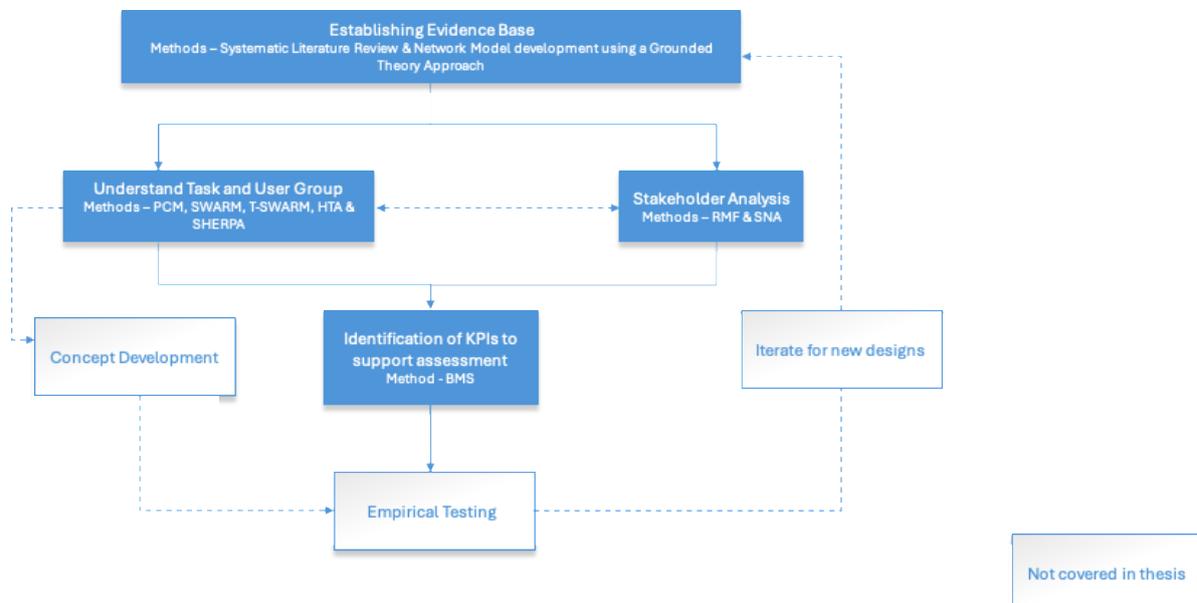


Figure 9.1 - Initial design framework reviewed by SMEs for the development of prototype system designs before a system has been development (other stages of the system lifecycle are not included).

### 9.2.2 Subject Matter Experts review

Seven SMEs were asked questions on the current practice when designing MASS (shown in Table 9.1) to understand the current guidance and processes. The interviews were conducted in person or on Microsoft Teams, which was used to record the interviews and generate transcripts. The SMEs that were interviewed have all been involved in the design and development of MASS at different stages; the majority of the SMEs were involved in the software development of the MASS HMIs and control systems, one of the SMEs was involved in developing the training for future operators, one SME was involved in the integration and testing of the MASS systems and one SME involved in maintaining MASS.

Table 9.1 – Questions on current practice and standards for MASS design and development.

Question no.	Questions on the current design processes
1.	What standards do you currently use to design and develop MASS? Are any of these Human Factors standards?
2.	<p>What information do you use when considering the design and development of MASS?</p> <ul style="list-style-type: none"> <li>○ What sources of information do you use?</li> <li>○ Where do you get the information from?</li> <li>○ How do you use the information?</li> </ul>
3.	<p>Are you aware of any Human Factors Integration processes associated with MASS?</p> <ul style="list-style-type: none"> <li>○ If yes, what activities are completed?</li> </ul>
4.	What challenges do you foresee surrounding the implementation of MASS?
5.	Have you ever been involved in any evaluations?
6.	Have these considered any HF considerations (e.g., workload, situation awareness, failure recovery etc.)?

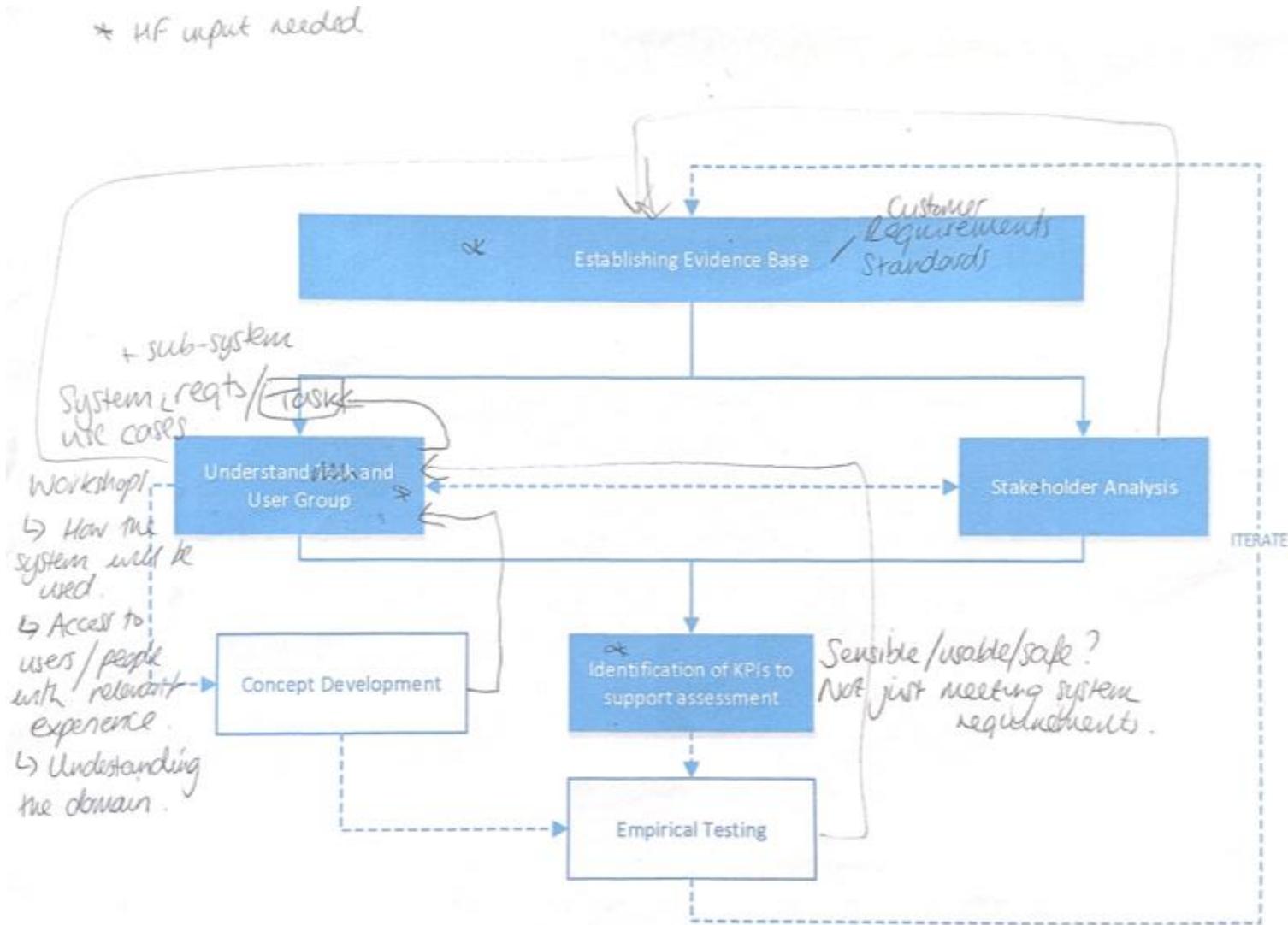


Figure 9.2 – Example SME feedback on the design framework.

After the questions the SMEs were then given an overview of the categories in the initial design framework that they were being asked to review. To explain how the initial design framework was developed SMEs were then given a brief overview of each stage in the design framework in terms of the methods used in the thesis and the outputs for each of these methods, to give them a more detailed understanding of what each stage of the framework was referring to. The SMEs were then presented with the initial design framework again and asked to give their feedback, including whether there any changes they would make to the design framework, whether any stages were missing or the order of the stages needed adjusting. Figure 9.2 shows the feedback from one of the SMEs on the framework, if the SMEs were in person they were given a framework to make notes directly on to and if they were online, they were given a PowerPoint slide that they could alter and make comments on. The feedback from the SMEs was then combined to create the final framework.

### 9.3 Results

#### 9.3.1 Current practice questions

##### 9.3.1.1 Current standards and information sources for MASS design and development

One of the key sources for current standards for MASS was existing maritime legislation (e.g., COLREGs) and the guidance given to manufacturers by the MCA. Whilst the current legislation has not been developed for MASS specifically, there are many aspects still applicable to their design as they are still ships. The Workboat Code Edition 3 published in November 2023, was mentioned as a source of standards for MASS, as it contains an annex (annex 2) specifically for remotely operated uncrewed vessels under 24 meters in load line length (Maritime Coastguard Agency, 2024). The annex states which sections of the code do not apply to uncrewed MASS due to the lack of crew and then the additional regulations that are required for remote operation. However, the annex does not include any regulation or standards specifically for human factors design or integration processes. The industry SMEs discussed the lack of standards and guidance for designing MASS HMIs and that the requirements are often vague for human factors, example interview quotes can be seen in Table 9.2.

Table 9.2 - Example quotes from the industry SMEs on current standards and guidance for MASS.

<b>Interview Quotes</b>
-------------------------

*“...from my experience mainly on the lack of human factors standards and guidance for designing the HMI...”*

*“We found that we were kind of struggling to get any guidance or standards or access to any information that helped us. So we designed the HMI as an engineering HMI.”*

*“...requirements tend to be a bit more vague on the human factors side of things...”*

Other SMEs discussed using the MASS UK Code of Practice developed by industry and academic partners to apply when designing and developing MASS. Human Factors is mentioned within the RCC operation section of the code of practice regarding promoting a just culture and considering individual factors such as fatigue, fitness for duty and training. The need to consider human factors when designing RCCs, including the layout of the control stations, is included, although no guidance is given on how to consider the human factors involved in designing RCCs.

The classification class codes were another source of standards and guidance for the design and development of MASS. Lloyd’s Register has produced a code for Unmanned Marine Systems (UMS) that states remote control panels for uncrewed MASS should be designed using Human Factors methodology (Lloyd’s Register, 2017). The DNV code has references to human sensing and ensures that these senses are replaced with other sources of information to improve operator SA but does not include any specific mentions of applying human factors methods in RCC design (DNV GL, 2018).

Lastly, Defence Standard 00-251 was mentioned as a source that contains Human Factors guidance when designing systems, it describes Human Factors Integration (HFI) processes that should occur along the Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal (CADMID) lifecycle (Ministry of Defence, 2021). It outlines a HFI process that contains six stages: user needs definition, system requirements definition, assess tenders, detailed system design, test and acceptance, and in-service feedback. The standard contains generic Human Factors User and System requirements, which more specific requirements can be derived within the system requirement definition stage. For the detailed system design stage, the standard highlights the importance of using a UCD approach and includes a list of example activities that could be performed across system analysis, design, and test and evaluation. The design framework developed here shows how a UCD approach can be used to generate human factors design principles when developing novel systems that currently lack standards and guidance.

### 9.3.1.2 Challenges surrounding the implementation of MASS

Regulations were suggested to be one of the biggest challenges for implementing MASS, as the regulators have the potential to inhibit innovation and the difficulties with the gap between technological advancements and regulatory guidance. As discussed in Chapter 8 there is currently a lack of regulations for the design of MASS. Another design challenge for MASS was the workload considerations due to the types of monitoring tasks that the operators are performing, there is potential for cognitive underload to occur during long periods of monitoring and dependent on shift length, which was also discussed in Chapter 5. To overcome this challenge, it was suggested by the SMEs that work is needed to ensure there are alerts at the right levels to gain an operator's attention.

There was uncertainty around realistic operational use cases, as it was suggested that currently there are many concepts, but the full business use cases have not been understood, especially on how MASS will be operated in a scenario with multiple MASS and crewed platforms, due to the difficulties in predicting the behaviour of a crewed platform. Also, the risks with other crewed platforms interacting with MASS when they can operate in more areas, as crewed ship operators may be unaware of how to interact with uncrewed MASS and be uncertain of their capabilities.

### 9.3.1.3 Integration processes and design evaluations

Four of the seven SMEs had been involved in Human Factors design evaluations, and some of the evaluations involved feedback in user trials and Human Factors workshops. However, one SME said, *"I'd say it [HF integration activities] doesn't get done routinely..."*, which demonstrates the need for Human Factors methods to be applied more during system development. The Human Factors workshops that were conducted involved experts reviewing the HMI which focused on the design of the HMI elements (e.g., colour palettes and chart colours). User trials were carried out where the users operated the HMI for a couple of different operational scenarios and then they responded to a questionnaire which asked them about the system's usability, to identify areas of improvement in the HMI design. Another SME had been involved in a similar usability study, which used eye tracking, workload assessment (NASA-TLX), situational awareness assessment (SART; Situation Awareness Rating Technique) and a system usability questionnaire (SUS; System Usability Scale). In addition to these measures, user feedback was also given at the end of the study, which identified further design issues.

One SME had been involved in evaluations for previous versions of the system where the physical controls of the onboard operator were assessed when the MASS was still being operated with a

minimal number of crew. The SMEs discussed the need for more of these types of activities to be included during the design process. For example, one SME said “...we get less engagement with users than we would like...we lacked the real detailed operational knowledge within the team of how they were going to use it” showing the need for further Human Factors input during the design stages. However, when projects overran or there were budget limitations, these types of activities were not carried out or the workshops were limited due to project pressures.

### **9.3.2 Final design framework**

The final design framework for developing a novel system is shown in Figure 9.3 which incorporates the SMEs’ feedback. Four of the SMEs felt that no changes were needed to the design framework, but minor adjustments were suggested by three of the SMEs. The main changes from the initial design framework shown in Figure 9.1 are that understanding the tasks and user group was split into two separate stages, understand the task and understand the user group and domain. This change was suggested as one aspect of the design will be understanding how the system will be used by the end user, the tasks and roles they will be required to perform, whereas understanding the user group will be more focused on developing the user requirements and understanding the types of end users for that system. In addition to understanding the user group, adding understanding the domain was suggested by several SMEs. Adding in understanding the domain was suggested as needing to be included as it is key that human factors experts that are involved in the design process have adequate knowledge of the maritime domain to be able to fully understand the users and the environment they work in.

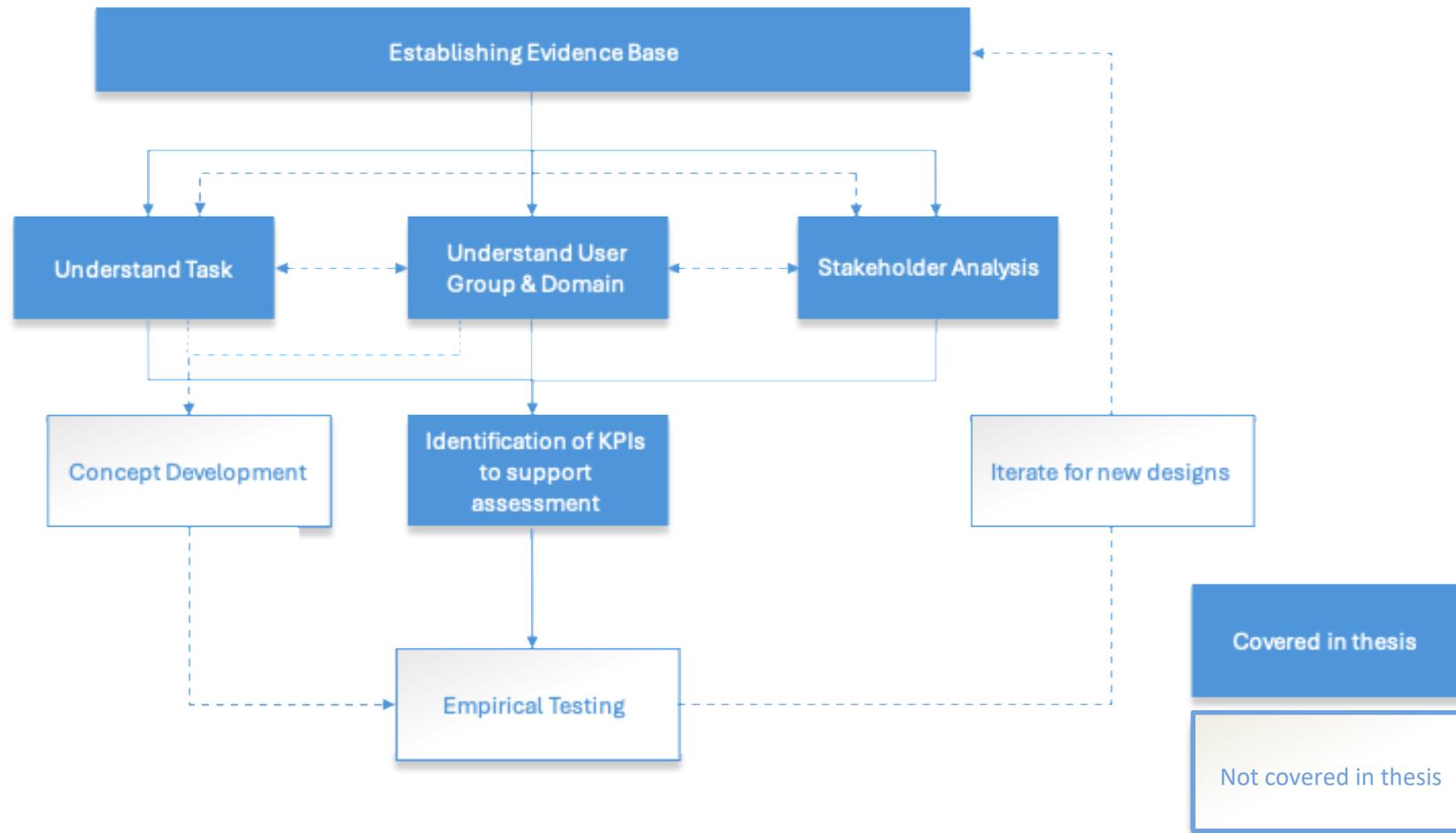


Figure 9.3 - Final Design Framework for the development of prototype system designs before a system has been development (other stages of the system lifecycle are not included) that combines the feedback from the SMEs. The last change suggested by the SMEs was to make the iteration loop a stage.

This suggestion was made to highlight the importance of revisiting any human factors analysis when new concept designs are generated and when the system is deployed and upgrades are made. It was mentioned that there was less human factors input during later stages of the system design and sometimes the new designs even went against the design recommendations generated in the human factors analysis of the previous design. So the stage iterate for new designs was included to show that this process will need to be iterated through as a system design develops and it may be necessary to go through these design stages again to reevaluate the new design concept. The SMEs also discussed the design stages and expanded on what they might include in the different stages beyond what has been covered by the methods in this thesis. For establishing the evidence base in addition to exploring the current literature to develop requirements, the stakeholder analysis stage is another key part of developing system requirements, and certain stakeholders may have specific customer requirements that need to be met.

The target audience for the system was discussed as being central to the design process so that the system is designed for the levels of experience of the end users. One SME involved in the training requirements of future operators discussed a risk is engineers will design the system assuming the end users have a certain level of knowledge, which could then increase the training burden or lead to a redesign being needed to make it more intuitive for the user. The SMEs discussed the need to ensure there is more engagement with end users to develop the use cases describing the tasks and sub-tasks involved, so the engineers gain more of an understanding how the systems will be used operationally leading to more intuitive designs. However, the challenges of finding end users of novel systems can reduce their ability to have that user engagement.

Stakeholders could change during the development and use of a system which would create the need to have a feedback loop between establishing an evidence base and conducting the stakeholder analysis. These changes could then affect the input into the rest of the design stages, for example, regulatory changes which are common when developing novel systems. When considering the identification of KPIs stage, SMEs suggest it will be important to understand the training requirements for the end users and conduct training assessments. There are currently difficulties in defining the training qualifications for MASS from existing maritime regulatory frameworks due to the differences in operations, as discussed in Chapters 7 and 8.

For the concept design stage, SMEs suggested that shorter feedback loops within the stages will be needed before progressing to the next stage to test parts of the system before beginning the integration testing of the different system components. The shorter feedback loops have not been included in the framework shown in Figure 9.3 but it is expected that at each of the stages these smaller feedback loops will occur before proceeding to the next stage. Lastly, SMEs commented that to further develop the design framework, it would be necessary to explore how this Human Factors

framework could be integrated with a more traditional engineering framework to show how the stages of each of the frameworks could be applied together in a cohesive framework.

## 9.4 Discussion

In this chapter, a design framework has been developed to show how the thesis methods can be used in the design process to ensure that a UCD approach is applied even at early stages when the users and system do not yet exist. The initial design framework was created by first using the chapters of this thesis; this framework was then reviewed by seven industry SMEs to produce the final design framework. Whilst other methods could be applied during the design framework stages, it has shown the main stages of a UCD process for future novel systems including MASS. The use of a UCD approach is necessary for maritime designs to promote safety and usability, however, there are currently no standards for designing maritime systems using UCD approaches (Hsieh et al., 2024; Veitch et al., 2021; Vu and Lützhöft, 2020b). It has demonstrated that these methods are suitable within the design framework and can be applied at early design stages of a highly automated and uncrewed system's development. The outputs of the methods show how the framework generates useful design principles and recommendations for developing concept designs. The framework also shows how to engage stakeholders in the design process of novel systems to capture the requirements of future users. As mentioned previously a challenge when designing a system can be ensuring that stakeholders understand the benefits of using Human Factors methods in early design development. This framework could be used to show the value in applying these methods and the types of outputs that can be generated with the stakeholder assistance in providing relevant SMEs to take part in the Human Factors activities to help facilitate stakeholder buy-in. Alternative human factors methods could be used instead of the methods outlined here in the different stages of the design framework; however these should be carefully considered to ensure they fit within the stages outlined in the design framework, and that different system lenses and aspects such as the users' mental models are still considered. For example, alternative sociotechnical systems analysis methods such as, System Theoretic Process Analysis (STPA) (Leveson, 2011), Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) and Event Analysis of the Systemic Teamwork Framework-Broken Links (EAST-BL) (Stanton and Harvey, 2017) could be used if the appropriate data can be collected or there is access to relevant systems and SMEs.

The final design framework shown in Figure 9.3, which combined the feedback from the SMEs, follows similar stages to those outlined in ISO 9241-210:2010, which has been used to design different maritime systems (Costa et al., 2017; Veitch et al., 2021; Vu and Lützhöft, 2020b). The main difference between the design frameworks previously outlined and the developed framework is that the framework has been broken into more detailed stages. For example, the stage understanding

and specifying the context of use, and specifying user and organisational requirements, consists of five stages in the framework rather than two. It was important to extend existing frameworks by also including establishing an evidence base as MASS are a novel system, as this allowed the identification of key factors within the HMT decision-making from the existing research in this field. This ensured that methods were selected to investigate all of the decision-making in HMT factors (see section 10.1 for further details of which methods were used to explore the decision-making factors in HMT). The addition of the iteration for new design stages suggested by the SMEs to ensure that any changes to the design were considered for any new human-machine interaction issues were considered is similar to the operational stage and operational user feedback loop suggested by Porathe (2016) to extend the ISO 9241-210:2010 process, as there is a need to reconsider a system's design based on this feedback and other operational changes that are made to the design.

Another key aspect of the framework was the stakeholder analysis, to consider the influences and requirements of all stakeholders within the system. This has been discussed as particularly important for novel systems such as MASS as they often lack the relevant guidance and legislation due to the gap between technological advancement and regulators (Kim and Schröder-Hinrichs, 2021; Yoshida et al., 2020). Regulations were mentioned as being a key challenge surrounding the design and implementation of MASS by SMEs and there is a lack of Human Factors guidance specific to MASS. As Chapter 8 has shown there is currently a lack of top-down influence within the UK MASS system due to the lack of formal regulations and guidance. SMEs mentioned various sources they use when designing MASS systems. However, Human Factors was only mentioned in the UK MASS Code of Practice and the Classification Societies Codes from Lloyds Register and DNV (DNV GL, 2018; Lloyd's Register, 2017; Maritime UK, 2020). However, they did not provide any guidance on the types of methodology that can be applied or make any of these activities mandatory (DNV GL, 2018; Lloyd's Register, 2017; Maritime UK, 2020). This issue has also been discussed in conventional ship design, as there is currently no requirement to ensure that UCD guidelines are used during maritime design (Grech and Lutzhoft, 2016). This framework provides guidance on how to apply Human Factors methods to create user-centred designs and whilst the methods do not produce standards for a novel system, they could provide a starting point for the development of future standards. It also shows why UCD approaches are needed when designing maritime and other safety critical domain systems and should be incorporated into future design standards. UCD would ensure that human-machine teaming issues have been considered and mitigated against during a design process by taking the first steps to understand the users requirements.

The other maritime UCD approaches applied semi-structured interviews to identify user-centred requirements (Costa et al., 2017; Kataria et al., 2015). The advantage of applying SWARM and T-SWARM is that they are semi-structured interview methods that use the theoretical underpinning of the PCM (Plant and Stanton, 2016a). The theoretical underpinning of the methods means that the

prompts within these methods are more likely to elicit a more detailed understanding of the decision-making processes within HMTs, as the prompts are focused on the key three components of decision-making, schema, action and world (Plant and Stanton, 2016a). The flexibility of SWARM and T-SWARM is also useful when applying them to novel systems, as hypothetical use cases can be used when the users and system do not exist, which has been demonstrated in Chapters 4 and 5, and in the aviation domain (Banks et al., 2021; Parnell et al., 2021b). This combines the retrospective approach of using the PCM to analyse an accident, shown in Chapter 3 in a similar domain and a predictive approach by modelling proposed decision-making to predict the types of human-machine interactions that could be seen to progress system safety (Hancock et al., 2009).

UCD approaches are important when designing any system, but particularly in the case of designing highly automated systems even though there is a common misconception that highly automated systems remove the human element (Kaber et al., 2002; Parasuraman and Wickens, 2008). Although, the human involvement may be less due to the higher levels of automation in the case of MASS operators still have an essential role in the system to intervene when required (Ahvenjärvi, 2016; Ramos et al., 2019; Veitch and Andreas Alsos, 2022). Therefore, it is necessary to design MASS systems with a user focus rather than a solely technology focus, to understand how the system can be designed to support their decision-making.

### **9.4.1 Evaluation and Future Work**

However, there are limitations to this design framework as it has not yet been fully validated as the later stages of the design framework, concept development and empirical testing stages have not yet been investigated. Similarly, there are limitations for all the methods included in the framework for further details of these limitations see the evaluation section in each chapter. Key limitations of the methods did include applying the findings from other domains, such as UAV, as there are differences in terms of the reduced decision-making time and operating the vehicle in three dimensions rather than two. There is also a hindsight bias when analysing accidents, but using accidents of operating a similar vehicle can be used to learn important lessons, as many of the Human Factors challenges are the same across domains. The application of SWARM and T-SWARM have shown the difficulties in eliciting schema data; However, this is a common limitation of any interview method. Even though there are limitations to each of the methods included within the design framework, the design framework provides a starting point for the development of a UCD framework for designing future uncrewed MASS systems, by applying these methods together some of the weaknesses of each method can be overcome by using this combination of them. Further work should explore identifying objective measures that could be used during the testing of concept designs, as the methods presented in the design framework are qualitative.

Future work will be required to explore how the design framework could be integrated with industry frameworks such as the design process outlined in Defence Standard 00-251, which is required to be used within the defence industry. Further research could also include applying the design framework to the design of other highly automated systems in other domains beyond maritime. The last stages of the design framework, concept development and empirical testing will be needed to explore what UCD methods could be used to develop the initial concept and how to test that design, to complete the application of the stages of the framework. After applying all the stages, it will be necessary to iterate for new designs and also to evaluate the complete framework and explore if any additional stages could improve the design concepts developed.

### **9.5 Conclusion**

A design framework has been created from the chapters of this thesis to show how the methods used can be combined to aid in the design and development of future MASS systems. The development of the framework shows how the Human Factors methods in the thesis can be used to design novel systems where access to experienced end users and real-world data is limited. It is a UCD process that could be shown to stakeholders to allow design teams to convey how Human Factors methods can aid the design and development of novel systems. The initial framework developed from the thesis was then reviewed by industry SMEs involved in the design and development of MASS systems, and minor changes were made to update the design framework to create a final framework.

In addition to reviewing the design framework, the industry SMEs were also interviewed on their knowledge of current standards and processes used in MASS design and development. The findings showed that there is often a lack of Human Factors input during the early stages of the design process, there is some guidance from Defence Standard 00-251 on the types of Human Factors activities that should be carried out when designing a defence system. However, it showed that currently there is a lack of Human Factors guidance, specifically for designing MASS. Various MASS guidance sources (MASS UK Code of Practice and Classification Society codes) mention using Human Factors but do not expand on the types of activities that should be performed. The SMEs discussed key challenges such as the difficulties in designing systems before regulations have been put into place and designing systems where operators are monitoring automated systems for long periods. This is often a key challenge found in designing novel systems, that due to their novelty there is a lack of standards and guidance as the systems are in development. Whilst the framework here does not necessarily address the lack of Human Factors standards, it demonstrates a process that can be used to capture user focused requirements when developing novel systems to help overcome interaction

issues that could be experienced in a HMT and provides a starting point for the development of such standards.

The final design framework consists of eight main stages: establishing an evidence base, understanding the task, understanding the user group and domain, stakeholder analysis, concept development, identification of KPIs, empirical testing and iterating for new designs. To extend this work further, it is necessary to explore how this design framework could be integrated with engineering frameworks currently used in industry, to show how it can be applied in industry design processes. In the next chapter, the decision-making factors in HMT model is updated based on the application of each of the methods included within the design framework. The next chapter shows how the findings from the other thesis chapters have demonstrated further interconnections between the decision-making factors.



# Chapter 10 Updating the decision-making factors in Human-Machine Teams model

## 10.1 Introduction

In this chapter the decision-making factors in HMT model developed in Chapter 2 will be updated to show how each chapter has investigated the seven decision-making factors through applying a combination of Human Factors methods. The chapter shows further evidence for some of the interconnections between each of the decision-making factors, as well as additional interdependencies between the factors. The findings have also demonstrated how the teams factors can be decomposed into further factors of communication and mental models. The research shows the findings from each of the methods can be used to extend understanding the influences on the HMT decision-making process.

### 10.1.1 The decision-making factors in HMT model

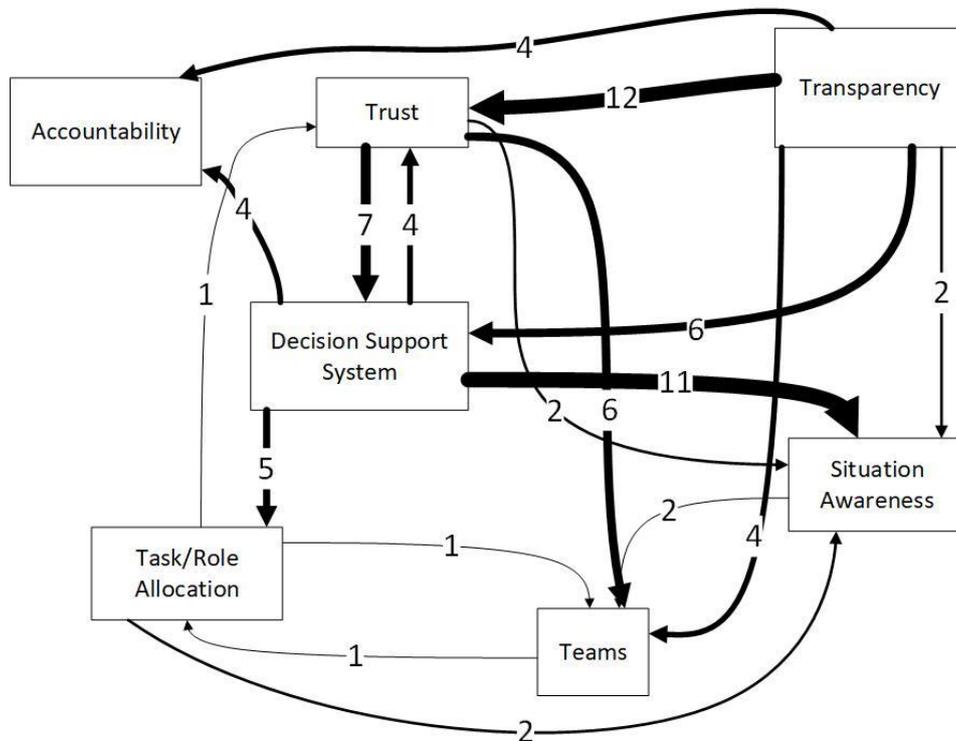


Figure 10.1– Decision-Making in HMT model showing the interconnections between the themes and the number of papers found for each interconnection.

## Chapter 10

The decision-making factors in HMT model shown in Figure 10.1 was initially developed in Chapter 2. Each chapter of this thesis has investigated each of the factors within the decision-making factors in HMT model and each method has corresponded to a different design stage as outlined in the design framework developed in Chapter 9. Table 10.1 shows the factors that were investigated in each chapter and the design stage that the methods could be applied based on the design framework.

Chapter 10

Table 10.1 - The factors investigated for each method that was applied for each stage in the design framework

Design Framework Stage(s)	Method	Decision Support System	Trust	Transparency	Mental Models	Communication	Task/Role Allocation	Accountability	Situational Awareness
Establishing an evidence base	Systematic Literature Review (Chapter 2)	Green	Green	Green	Green	Green	Green	Green	Green
Understand Task/ Understand User Group and Domain	Accident Analysis using the PCM (Chapter 3)	Green	Green	Green	Green	Green	Green	Green	Green
	SWARM (Chapter 4)	Green	Green	Green	Green	Green	White	White	Green
	T-SWARM (Chapter 5)	Green	White	Green	Green	Green	White	White	Green
	HTA & SHERPA (Chapter 6)	Green	White	Green	White	Green	Green	White	White
Stakeholder Analysis	Risk Management Framework & Social Network Analysis (Chapter 8)	Green	White	White	Green	White	Green	Green	White
Identification of KPIs to support assessment	Behavioural Markers System (Chapter 7)	Green	Green	Green	Green	Green	Green	White	Green

## 10.2 Updating the Decision-making Factors in Human-Machine Teams Model

The decision-making factors in HMT model was updated based on the findings from applying each method in the design framework. The findings from each chapter were reviewed as the papers were reviewed in Chapter 2, to add further connections to the decision-making factors in HMT model. Figure 10.2 shows which chapters contributed to the existing connections within the decision-making factors model (red connections) and which chapters showed evidence for new interdependencies within the model (blue connections). The results of reviewing the findings from each chapter were then combined with the additional connections within the initial decision-making factors in HMT model to create a final updated model shown in Figure 10.3. The 'Teams' factor included in the initial model was split into two factors, 'Communication' and 'Mental Models' based on the findings from Chapters 3, 4, 5 and 7, which showed the importance of communication and the development of a shared mental model between the operator and the system in supporting teamwork behaviour. The application of the PCM framework in Chapters 3, 4 and 5 has demonstrated how key mental models are within decision-making in a HMT. The development of the BMS in Chapter 7 has also shown that a shared mental model is needed and that communication is an essential behaviour for effective teamwork in a HMT. The interconnections to and from 'Teams' from the initial model were reassessed and split into 'Communication' and 'Mental Models' connections.

In Chapter 3, the analysis of the UAV case study showed how the pilot's mental models influenced their SA, as they believed the UAV had landed due to the view on the camera feeds, but the pilots had lost their SA. There was also a lack of a clear command structure, as their roles were unclear it reduced their ability to communicate effectively within their team. The case study showed the need to consider the design of DSSs and the saliency of their alerts to ensure effective communication with the operator. Conducting the HTA and SHERPA showed that a large number of errors were related to not checking information on the HMI/DSS and remedial strategies were suggested for how the design of the DSS and the transparency of that design could be used to improve communication.

# Chapter 10

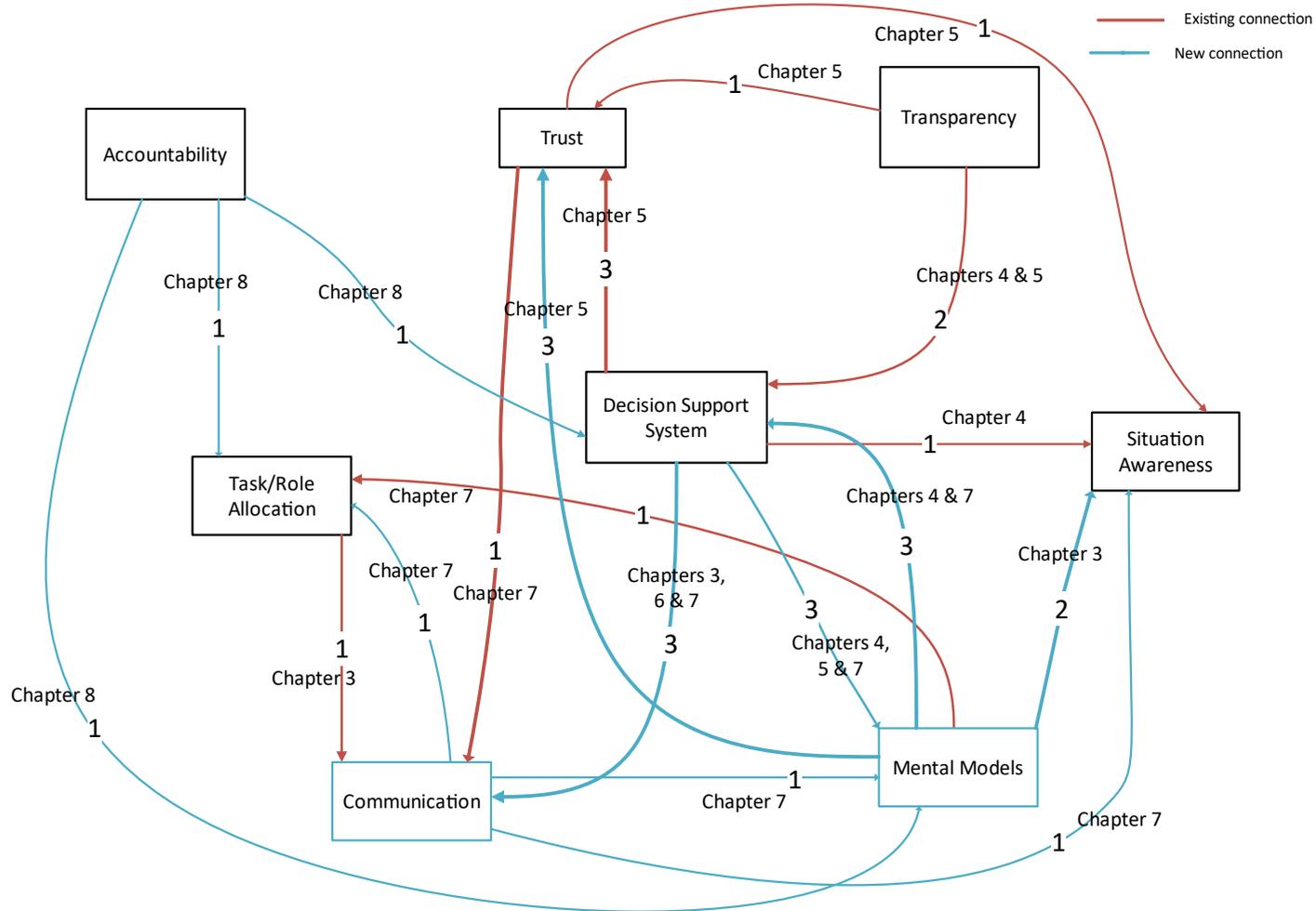


Figure 10.2 - Decision-making factors interconnections seen in findings from each thesis chapter.



that could be incorporated into a system design, such as how communicating intent could aid the operator in developing a shared mental model and creating a mental model of the team for a machine teammate to improve the teams shared decision-making.

The RMF and Social Network Analysis of the UK MASS system showed how there are many actors within the system and there is accountability and responsibility at each of the system levels.

Connections were added from the accountability factor as there is a need for clear guidance from regulators to outline the roles and responsibilities of the members of the RCC team and system for different automation levels. Training guidance is needed for operators from regulators so that appropriate training is conducted to allow operators to form mental models from their training.

Lastly, it is important to ensure that UCD principles are followed when designing DSSs, as outlined in this design framework.

### **10.3 Summary**

In this chapter, the decision-making factors in HMT model was reviewed and the model was updated. Eight decision-making in HMT factors were added based on the findings of the other chapters of the thesis. The initial decision-making factors in HMT model consisted of seven factors: Decision Support Systems, trust, transparency, task/Role Allocation, teams, SA and accountability. This approach has demonstrated how a mixed-methods approach was used to explore each of the seven factors in MASS operations. The findings of the application of the methods showed further evidence of the interconnections shown in the initial model as well as additional interconnections between the decision-making factors to create the updated model. Eight factors were included in the updated model with the factor teams being split into communication and mental models as these were both key factors seen the findings from the other chapters. The updated decision-making factors in HMT has highlighted the importance of developing two-way communication within the HMT and support the development of a shared mental model between the operator and the system. It has also shown how each of the factors needs to be considered in the design of future MASS decision support systems. The next chapter summarises the findings of the thesis and its contributions to knowledge.



## Chapter 11 Conclusions and Future Work

### 11.1 Introduction

This final chapter will give an overview of this thesis and discuss how it has met the objectives set out in the introductory chapter (Chapter 1). After a summary of the findings, the theoretical, methodological and practical contributions will be discussed, including the identified areas for further work.

### 11.2 Summary of findings

#### 11.2.1 Objective 1: Understanding factors involved in decision-making in HMTs and specifying design considerations

The first objective of this thesis was to understand decision-making in HMTs and how it previously has been investigated in the maritime and other similar safety-critical domains (e.g., aviation) to specify design considerations for MASS. Chapter 2 (published: Lynch et al., 2024) discussed the challenges in operating MASS and other uncrewed and highly automated systems, such as the lack of SA and issues with under and over-reliance on automated systems (Mallam et al., 2020; Man et al., 2016; Porathe et al., 2014). It showed the difficulties for decision-making due to the reduced human involvement in the decision-making process, as more of the decision-making is shared with the automated systems. However, the human involvement in the system may become more crucial as they will be needed to handle abnormal or emergency situations.

A grounded theory approach was applied to the decision-making in HMT literature; the details of the procedure and findings are outlined in Chapter 2. Seven key factors were identified: DSSs, trust, transparency, teams, task/role allocation, SA and accountability. For definitions of these factors see section 2.3.3. For each of the seven factors, design considerations to support decision-making in HMTs were also generated from the literature, and areas for future work were suggested. The seven decision-making factors formed the foundation of the research programme, while the other chapters of this thesis applied a variety of methods to investigate each of these factors.

The literature was then reassessed to explore the interconnections between the seven factors to develop a network model for the decision-making factors in HMTs. The application of a case study of a UAV accident (detailed in Chapter 2) demonstrated the interdependence of these factors in a real-world scenario and showed each factor's importance in the HMT decision-making process. Therefore, it was necessary to investigate each of the decision-making factors within the model in the other

thesis chapters to further explore their interdependencies and to highlight design considerations for each factor.

The UAV accident case study described in Chapter 2 was then modelled using the PCM in Chapter 3 (published: Lynch et al., 2023) to explore how decisions are made within a HMT, by considering aspects such as the system's design and how it can affect decision-making. Modelling decision-making using the PCM demonstrated how an operator's mental models from learnt behaviours can influence their decision-making and how the systems were used in unanticipated ways causing the operator to lose SA. The findings showed the crucial role of HMIs in developing an accurate shared mental model in the HMT, so that operators can maintain SA and how in this case camera feeds were distracting to the operator. The case study showed how the lack of proximity to an uncrewed vehicle may make decision-making more challenging due to the need to rely on digital information, which could be perceived incorrectly and lead to erroneous decisions. This further demonstrated how the HMT decision-making process can be influenced and highlighted lessons that could be learnt from other domains.

The decision-making factors in HMT model was updated based on the findings of the other chapters of the thesis (detailed in Chapter 10). The findings of the chapters highlighted HMT communication and mental models, so the factor Teams from the initial decision-making factors in HMT model was split into communication and mental models. Additional interconnections were also added between the factors and the findings showed further evidence for some of the existing interconnections within the network model, connections such as between DSSs and trust, and transparency and DSSs, which demonstrates the need to consider these factors during DSS design. The new connections in the model show the importance of considering how mental models in the HMT are influenced by other factors such as communication and system design, and then how mental models then affect other factors trust and distributed SA in the HMT.

To aid industry in developing future MASS systems design considerations were suggested in Chapter 2 for each key theme, to show what they may need to consider during the design process these considerations are shown in Table 2.2, see section 2.3.3. In addition, recommendations for MASS were also generated from exploring a UAV accident in Chapter 3, for specific details of these recommendations refer to sections 3.4.1, 3.4.2 and 3.4.3.

### **11.2.2 Objective 2: Investigating the tasks and decisions involved in operating MASS using Human Factors methods**

The second objective built on the understanding of the HMT decision-making process by investigating the tasks involved in the operation of MASS using a variety of Human Factors methods. The methods were used to generate design principles and mitigation strategies to support decision-

making in the HMT. Firstly, to explore the decision-making involved in the operation of MASS, SWARM which is theoretically underpinned by the PCM was used in Chapter 4 to interview MASS operators and other SMEs. The data collected using SWARM was coded using the SAW taxonomy to analyse the results in terms of the three main components of the PCM. This approach showed that design and training principles supporting the components of the PCM (schema, action and world) can be generated before a system exists. It was found that the design and training principles for decision-making were in four key areas of MASS operations: developing expectations of the automated systems, supporting the operator's supervisory role, processing digital information and handling system faults.

For details of the design principles for each key area, see section 4.4. The design principles generated from the SWARM data demonstrated the importance of considering the types of digital information that will need to be incorporated into a HMI design to support operators in obtaining the necessary world information to be able to understand the situation. The training principles also suggested how operators' schema could be developed in a training programme to aid their ability to make decisions. The results showed that decision-making whilst in a supervisory role will be challenging for operators due to the potential for them to become passive monitors and because they will be reliant on predominantly digital information to make decisions.

Building on the work in Chapter 4, Chapter 5 investigated how the development of trust can be supported for MASS operations. As identified in Chapter 2, trust was found to be a key factor in the decision-making factors in HMT model. This was achieved by using T-SWARM, an extension of SWARM, to understand what factors influence trust in decision-making using the PCM framework. These seven key SAW sub-types found were: "Display Indications", "Technological Conditions", "Situation Assessment", "Artefacts", "Direct Past Experience", and "Navigate". The principles developed from these key SAW sub-types highlighted the potential trust issues for HMTs, as operators have to rely on digital information. The results showed the difficulties that could be experienced if they cannot verify the digital information and to trust this type of information is strongly against their previous maritime training. Other findings from the application of T-SWARM were that operators will need an understanding of the system's behaviour across multiple scenarios to achieve that calibrated trust. Design principles were also suggested to aid operators overseeing the automation in checking that it is working as anticipated and giving operators an understanding of the limitations and capabilities of different sub-systems.

To explore what mitigation strategies could be suggested for operating MASS from RCCs, an error analysis was conducted in Chapter 6. HTA was used to describe the tasks involved in operating an uncrewed MASS from an RCC for an environmental survey. The HTA was generated at an early design stage using system documentation and by observing software testing to show how the error analysis

can be conducted before the system is fully developed. The results of the HTA showed that only 15% of the tasks related to normal operations and that the operator would have minimal interaction with the system, only starting and stopping the survey and monitoring its progress, 71% of the normal operation tasks were monitoring. The results of applying SHERPA showed that there were 510 errors that could occur whilst conducting the tasks for a survey, although 94% of the errors had a low likelihood with various criticality ratings. The results generated design-based mitigation strategies, which mainly focused on increasing the saliency of alerts, prompting operators to make necessary checks in response to alerts and for the design of the different HMI elements.

The findings from Chapters 4, 5 and 6 have shown how a mixed methods approach can be applied to suggest design principles and mitigation strategies for the design of future MASS systems. The design principles from Chapter 4 are shown in Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6 (see section 4.3.2), which show the information requirements of the operators to support their mental models and how operators can be aided in their actions. Design principles that could be used to specifically support trust in future systems are outlined in Figure 5.3 and Figure 5.4 (see section 5.3.2). Mitigation strategies that focus on the HMI design are shown in Table 6.7, see section 6.3.2 for further details of these recommendations. These design principles and mitigation strategies should be implemented or considered by industry when creating new HMI designs and concepts of operation.

### **11.2.3 Objective 3: Exploring HMT behavioural competencies**

To meet this objective a BMS was developed for a HMT, which describes the behavioural competencies that will be required by both the human and machine teammates within the HMT to work effectively as a team. As identified in the initial decision-making factors in HMTs model developed in Chapter 2, humans and machines working collaboratively (Teams) was a key factor in the decision-making process. The development of the BMS in Chapter 7 showed that many of the behaviours relevant to human-human teams were also relevant to both sides of the human-machine interaction. The BMS included eight main behavioural categories (see Chapter 8 for a detailed description): closed-loop communication, decision-making, leadership, performance monitoring, backup behaviours, adaptability, SA, shared mental models and trust. However, it was demonstrated that adaptations were required to make the behavioural markers applicable to a human-machine interactions. The set of behavioural markers for operators interacting with systems could be used in training future operators to ensure they have the competencies to be effective teammates. For machine teammates, it showed the need to consider how the system could be designed to promote the identified teamwork behaviours to aid the HMT in completing their goals. The behavioural markers that could be implemented in future designs are outlined in Appendix F, however further work will be required to test and validate these behaviours to understand how each behaviour

influences HMT performance and how they could be best implemented into a system's design. These markers could be tested in a synthetic environment to test multiple implementations of the behaviours before more advanced system concepts are developed.

#### **11.2.4 Objective 4: Conduct a sociotechnical analysis of the MASS system**

In Chapter 8, a sociotechnical analysis of the UK MASS system was conducted to investigate how the actors within the system affect the safety of MASS operations. This sociotechnical system approach was used since one of the key decision-making factors discussed in Chapter 2 was accountability, and when considering accountability it is important to consider all the parts of a sociotechnical system. This work showed that there is a need to consider what recommendations can be made across the system levels, to extend the findings from the other chapters which focused on the lower system levels. The application of the approach demonstrated the complexity within the maritime domain as 60 actors were found in the current UK MASS system. The results of the Social Network Analysis between the actors showed that the actors with the highest degree of influence within the current system were those within the industrialist level of the system, rather than the actors at higher system levels who might be expected to have the highest degree of influence within the system, such as the international committees, national committees and regulators. The second social network of a potential future MASS showed that implementing MASS specific regulation and guidance for training from the higher level actors could improve the systems resilience.

It has been suggested that there is a need for a regulatory framework for MASS that has proactive measures to reduce the gap that forms between the development of technology and the regulatory frameworks to ensure MASS can be operated safely (Hoem et al., 2021; Kim and Schröder-Hinrichs, 2021). The findings were used to suggest system recommendations for all the hierarchical levels within the RMF. For the international committees, national committees and government levels, the recommendations included the development of a regulatory framework and an outline of the roles and responsibilities of the master of a MASS when using different levels of automation. Other system recommendations included ensuring industrialists test the systems sufficiently, providing users with clear guidance on a system's operational constraints and using user-centred design principles when designing MASS systems. The sociotechnical systems approach showed that recommendations can be made at all of the MASS system levels and that there are many actors within the system. For the specifics of the system recommendations for all the hierarchical levels see Table 8.4 in section 8.4 in Chapter 8.

### **11.2.5 Objective 5: Develop a design framework for the design and evaluation of future MASS systems**

The final objective of the thesis was to develop a design framework that could be used by industry when designing novel systems such as MASS. The UCD framework was developed in Chapter 9 which showed how Human Factors methods used in the thesis can be applied to generate design concepts for novel systems early in a system's design life cycle. The initial design framework developed from reviewing the Human Factors methods in this thesis was then reviewed by industry experts to explore how it could be applied during the design framework. The industry experts feedback on the design framework showed that it could aid engineering design teams in applying Human Factors earlier in a system's design and ensure that a user-centred design approach could be followed to optimise HMT decision-making. The final design framework consisted of eight main stages: establishing an evidence base, understanding the task, understanding the user group and domain, stakeholder analysis, concept development, identification of KPIs, empirical testing and iterating for new designs. Each stage showed how user-centred approaches could be used to develop design considerations and principles, and generate remedial strategies to aid in the design and development of future MASS systems. A methodological contribution is that the design framework developed has shown how methods that use micro, meso and macro system lenses can be integrated together into a coherent process to ensure decision-making is supported and safety is considered at all the levels of the sociotechnical system. To ensure that the framework is applied in industry it should be incorporated into their existing system processes. By incorporating it into existing process it would ensure that human factors is considered at each stage of the relevant design process and the recommendations made at each design stage can be integrated into the design rather than be considered as a separate to the development process.

## **11.3 Evaluation**

Research methods have different strengths and limitations depending on the constraints of the research project. One of the challenges of conducting research in MASS was that it is a novel domain and therefore there is limited access to systems, operators and other SMEs. In addition, many of the MASS under development are military systems, which limits access to systems, operators and SMEs. However, these barriers were overcome by finding civilian MASS operators with experience in other sectors, such as oil and gas and training of future operators and other SMEs who were able to apply their knowledge to a civilian use case. Other limitations due to the novelty of MASS were the lack of case studies and use cases, although the industry sponsors of the project were able to assist with a use case that provided the basis of the interviews and task analysis.

Due to these access challenges this thesis applied mainly qualitative approaches as access to simulators and observations of trials was limited, therefore, there were difficulties in collecting any quantitative data. However, to overcome these challenges qualitative approaches were applied such as using a case study and conducting interviews to collect data, as these allowed flexibility in their application to hypothetical scenarios of operating a novel MASS system. A grounded theory approach (Braun and Clarke, 2006) was applied to generate the initial decision-making factors in HMT model, as it is a flexible method which can be tailored to the research objective. Grounded theory has limitations as it is a qualitative method, as the analysis can be affected by the subjectivity of the researcher. However, Braun and Clarke (2006) outlined principles for conducting qualitative analysis to improve its application when generating themes from qualitative data. Inter-rater reliability analysis was conducted to assess the reliability of the coding of each theme from the literature and the interconnections between the themes due to the subjective nature of the coding process to acknowledge the limitations of the method. The decision-making factors in HMT model's ecological validity has initially been assessed using a UAV case study, which showed how the factors could be seen in a real-world decision-making scenario. However, it needs to be evaluated against real-world behaviour in MASS operations to fully assess its ecological validity. There are limitations when analysing case studies as the findings cannot be generalised due to the specific circumstances of a case. However, analysing case studies can provide a useful method for developing knowledge and understanding on how safer systems can be designed, even though it may only be one case (Flyvbjerg, 2011).

SWARM and the extension of the method T-SWARM were used as a primary source of data collection. One of the main limitations of these methods is the difficulties in eliciting schema data (as discussed in Chapters 4 and 5), which resulted in much lower schema references in the SWARM and T-SWARM data. However, this is a common limitation of interview methods since schemas are often unconscious, therefore schemas are challenging to elicit as the decision-maker may be unaware of their schema and how it has influenced their decision-making (Neisser, 1976). Another challenge in using interview methods was recruiting MASS operators, as currently there are very few MASS operators, and only a few operate uncrewed MASS as MASS is a developing technology, so a small sample size was used. However, this approach has shown that SMEs can be valuable when operator access is limited, or they do not exist, MASS are not yet used extensively operationally, and none of the operators interviewed in Chapters 4 and 5 were operating an uncrewed MASS using high levels of automation.

The development of the BMS has limitations as it was developed from multiple domains and therefore some of the behaviours may not apply to operating uncrewed MASS from an RCC or necessary behaviours may not yet be included. However, SME reviews were used to mitigate this limitation, and an initial validation was carried out by observing UAV RCC operations to take a first

step into showing which types of behaviours are present in a HMT. To assess both operators and MASS systems, additional measures will be needed to evaluate their performance due to the subjectivity of rating behaviour through observation, quantitative measures would also need to be incorporated into an evaluation. Applying quantitative measures during the early stages of a design process can be challenging, but once designs have functionality, appropriate quantitative measures should be used such as assessing the operators workload, SA and the usability of the system (Stanton et al., 2017b).

## **11.4 Future work**

The research presented in the thesis has extended the knowledge of how HMTs make decisions and the underlying factors that affect this process by using Human Factors methods, which consider system design from the user's perspective. The implications of this research have suggested various areas for future work, which are summarised below.

### **11.4.1 Further exploration of the decision-making factors in HMT model**

This thesis has aimed to understand decision-making in HMTs and to show what factors need to be considered when designing MASS systems. The development of the decision-making factors in HMT model was used to demonstrate the factors involved in decision-making and how they influence the other factors. Further work should seek to validate the model using simulation data from testing MASS systems or real-world data from uncrewed MASS operations once these systems are used more extensively. The findings of this thesis have shown there are additional connections between the factors identified within the model (as discussed in Chapter 9). Further research is needed to explore these connections and how these factors can be applied to optimise a decision support system's design.

For example, areas for future research could be comparing an operator's level of trust when operating using similar navigation systems on a conventional vessel compared to when they are operating an uncrewed MASS to explore the differences in trust when they lack physical cues. The findings of Chapter 5 showed that in their training of mariners, they are often taught not to trust any digital information, which may affect their ability to trust MASS systems. How a MASS decision support system is designed to communicate to promote the formation of accurate mental model development and SA should be further investigated, particularly the types of communication used (e.g., visual, audio and haptic).

The operator's and the HMT shared mental model was found to be a key factor in the development of the decision-making factors in HMT model. The mental models factor was shown to be connected

to all of the other seven factors within the model; it will be important to explore further how future systems can be designed to aid operators in creating mental models more intuitively. The findings have shown the difference in the types of information that the operator will have available to build their mental model. Therefore, there is a need to investigate the application of different technologies for the design of DSS. Virtual reality should be further explored in the design of future MASS systems as it has already been demonstrated that it can improve a MASS operator's SA (Lager et al., 2019). Conceptual designs for the use of virtual reality for MASS designs have already been suggested (Reitmann and Jung, 2024). However, further research is required into how these types of systems should be implemented so that they support the operator's decision-making whilst also considering the potential for unintended consequences, including how they may influence other factors, such as the operator's trust. Virtual reality has been investigated in other domains, such as the operation of highly automated vehicles, but it has shown that more research is needed as virtual reality technology advances and improves in its ability to more accurately represent the environment it is simulating (Kalamkar et al., 2023).

#### **11.4.2 Elicitation of schema**

The findings of this thesis have shown that insights into MASS operators' decision-making can be gained using qualitative methods such as SWARM and T-SWARM. However, their application has shown the challenges in eliciting schema data as the results showed much fewer references to schema versus the world and action components of the PCM. SWARM and T-SWARM were selected to generate decision-making data as it has previously been researched how it can be applied to future system design (Banks et al., 2020; Parnell et al., 2021b). Future research should explore how to improve the elicitation of schema data when investigating decision-making using the PCM framework. For HMT decision-making mixed-methods approaches could be applied by using observations to understand what information a user could use to build their mental model. Once a design has been further developed and can be simulated, it could gain more insight into a user's mental model as well as doing prospective and retrospective interviews using SWARM.

#### **11.4.3 Further development and validation of the Behavioural Markers System**

The BMS in Chapter 7 will require further development to explore how machine agents can display the behaviours identified for HMTs. One key behavioural category in the BMS was shared mental model development between the human and machine teammates. Further research should explore how a system could create a representation of an operator's mental model using technologies such as artificial intelligence, to develop existing system designs to investigate how such a representation could be used to configure the system to adapt to the operator's mental model (Grimm et al., 2023). To understand the development of HMT's shared mental models beyond behavioural observation,

SWARM and the theoretical framework of the PCM could be used to explore the perceptual processing of machine teammates to show how machine mental models are generated and how an operator's mental model could be integrated into the system's decision-making. It has been highlighted that there are currently gaps in determining the best practice for eliciting data on shared mental models within a HMT (Andrews et al., 2023). Therefore, SWARM could be used to investigate how a system could gather information about their human teammate's mental model, then combine the mental models and create that shared mental model within the HMT.

Another avenue for further research and to extend the performance monitoring behavioural category in the BMS would be to explore how technologies could be used to monitor the operator performance so that the tasks and roles in the HMT can be reallocated as needed. Action recognition has been suggested as one technique that could allow a machine teammate to monitor the performance of a human operator (Mehak et al., 2024). Other monitoring methods have investigated eye tracking and task performance data to explore their utility in predicting human performance, trust and intent (Hulle et al., 2024). However, further monitoring techniques should be examined to identify which are optimal for different types of MASS operations and what other implications such technology could have on the HMT's decision-making process. Similarly, the ability of the machine teammate to provide backup if the operator is overloaded or engage the operator if they are underloaded should be researched further to determine how the system could estimate the operator's workload and what strategies should be implemented to redistribute the workload within the HMT (Burian et al., 2023; Giolando and Adams, 2024; Heard and Adams, 2019).

Further validation is also needed to ensure that the relevant teamwork behaviour for a HMT has been captured. This validation could be carried out when there is more available data on real-world uncrewed MASS operations or data could be generated in a synthetic environment, through testing and training using MASS system simulators to see which of the behaviours are seen and whether there are any additional behaviours to include within the BMS for HMT. Future work should also consider the behaviours seen in the HMT during the response to abnormal situations, as this was a limitation of the initial validation when observing the UAV operators, as these scenarios were carried out in normal operating conditions. The limitation of only observing normal operations is that some of the behaviours would not have been seen, as they are less relevant to normal operations (e.g., adaptability and backup behaviours) and as a key role of a MASS operator will be dealing with abnormal scenarios is important that they can demonstrate appropriate behaviours (Liu et al., 2022b; Mallam et al., 2020).

The BMS could be applied to other domains where decision-making is shared between human and machine agents, the initial validation carried out in Chapter 7 has shown its validity in operating uncrewed aerial platforms and has been created from BMS from multiple domains and is non-specific

to maritime. Also, the BMS could be used in the design and evaluation of other systems that involve a HMT including automated driving, uncrewed ground vehicles and UAVs.

The BMS developed could also be used to create a training syllabus for future MASS operators, although it is important to consider other mitigation strategies focused on aspects of system design, training operators' non-technical skills could improve the safety and performance of the HMT (Salmon et al., 2023; Young and Steel, 2017). The training syllabus could focus on the nine behavioural categories identified in the BMS: closed-loop communication, decision-making, leadership, performance monitoring, backup behaviours, adaptability, SA, shared mental models and trust. Simulator training has been suggested for training bridge crews using a BMS to evaluate the mariners (da Conceição et al., 2017). Simulator scenarios could be used to evaluate an operator's non-technical skills in abnormal situations by developing appropriate simulator scenarios based on the behaviours identified within the BMS for HMTs.

#### **11.4.4 Extending the Design Framework**

The design framework developed in Chapter 9 has demonstrated a process of generating design principles and considerations in the early stages of the development of a system, even before the users of the system exist. Further research is needed to explore extending this framework to include other methods that could be applicable, particularly around developing the design concept from the other findings as this has not been included in this thesis. Similarly, the empirical testing stage was not included and would require further investigation into the types of testing that could be used to evaluate the concept designs. For example, techniques such as Wizard of Oz (Kelley, 1985) and storyboards (Truong et al., 2006) could be used to evaluate the system design, which could be generated from the design principles from the application of SWARM and T-SWARM before it is further developed and functionality is implemented.

Further validation is also needed to test the design framework in other domains as well as MASS; this design framework could be applied to other future sociotechnical systems that do not have existing users but are safety-critical and require a user-centred approach, such as future bridge designs (Grech and Lutzhoft, 2016) and other uncrewed platforms (Calhoun et al., 2018; Lingam et al., 2024).

#### **11.4.5 Decision Support System design for operating multiple uncrewed platforms**

Whilst the focus of this thesis has been on the interaction between one operator and one MASS future work needs to explore what other factors could influence the decision-making process of a HMT when operators are operating multiple MASS from an RCC. The design of future human-machine interfaces for the control of multiple uncrewed platforms needs to consider how to aid operators in achieving an appropriate level of SA when operating multiple vehicles, as it could further

increase the potential SA issues when using high levels of automation and operating beyond line of sight (Saffre et al., 2021). In some applications, it is likely that MASS will be used in a HMT consisting of multiple types of uncrewed platforms, including UAVs, uncrewed ground vehicles and uncrewed underwater vehicles (Calhoun et al., 2018). Therefore, further research will be needed to consider how the HMT decision-making process may change when operating multiple types of uncrewed vehicles from the same RCC and how interfaces can be designed to integrate information from multiple types of vehicles.

Other applications of operating multiple uncrewed platforms have explored having multiple operators with shared responsibility for several uncrewed platforms (Roth and Schulte, 2020). Operating multiple uncrewed platforms with multiple operators could impact HMT decision-making, as it introduces more complexity in how the tasks and roles are dynamically allocated between the machine and human agents and how decision-making is shared. Further research should explore the development of a shared mental model between a HMT consisting of multiple human teammates and machine teammates. The PCM has been applied with a network-based approach to human team decision-making to show the team decision-making process by connecting the components of the PCM of each team member in a network (Plant and Stanton, 2014b). Future work could apply the PCM using a network-based approach to show the decision-making process of the human team members and the machine team members and explore the interaction issues that might occur in a larger HMT.

#### **11.4.6 Critical decision-making training**

Another avenue that could be explored is the use of a decision aid based on the theoretical framework of the PCM as suggested by Plant (2015) could aid operators in developing their decision-making skills and preparing operators for dealing with critical incidents. Whilst the decision aid was designed for aeronautical decision-making, as demonstrated in Chapter 4 only a few adjustments were required to the SAW taxonomy to make it relevant for the maritime domain, so the aid could also be adapted for MASS operations. Decision training has been implemented in aviation to aid pilots in making critical decisions (Mohan et al., 2024; Plant, 2015). It has also been suggested for training officers of the watch training, but it would be an extension to their current formal training (Chauvin et al., 2009). Decision training using simulator-based training has been shown to aid novice mariners' ability to recognise and respond to collision avoidance scenarios (Türkistanli and Kuleyin, 2022).

Decision training using the PCM would give the training a theoretical foundation. Applying the PCM to decision training could allow operators to develop an appropriate schema for responding to abnormal events. The results of applying SWARM showed that current mariners already have heavily

learnt schema, decision training should be explored as a method that could allow them to be more aware of their schema and how it might impact their decision-making. Similarly, decision training could provide operators with an opportunity to develop schema for abnormal situations, such as types of system faults. This could give operators a greater awareness of the key cues in those abnormal scenarios and allow them to understand more about the system's functioning. In addition to simulator training, the PCM could be applied as a framework for reflecting and evaluating their and other decision-making during an exercise (Plant, 2015). Reflecting by using the PCM framework could demonstrate any conflict between the operator's mental model and the actual situation and if there is a conflict between the operator's and the system's perception of a situation.

## **11.5 Closing remarks**

Before carrying out this research for this thesis my knowledge of the maritime domain and the use of MASS was limited. My experience conducting this research has shown me that there are many challenges in making decisions in the maritime environment due to its complexity and the types of technologies being used. These challenges only get harder when an operator is removed from the ship entirely and is operating a ship out of their line of sight. I have also had the opportunity to contribute to an information paper on the behavioural markers work that has been submitted to the International Maritime Organisation's sub-committee on Human Element, Training and Watchkeeping. Hopefully this will aid in starting the discussions on considering the necessary behaviours required for HMTs and future submissions will focus on the teamwork behaviours of the automated to aid in the development of future MASS standards. Often when reviewing maritime accidents, the cause is attributed to 'human error' and it is quoted that 80% of maritime accidents are due to 'human error' (Hoem et al., 2018). This thesis has aimed to ensure that user-centred design approaches are applied in the design and evaluation of future MASS systems by using the developed design framework to take the focus off the individual operators and focus on how systems can be designed to allow them to perform their jobs more effectively. The need to consider the users in the design of systems is the core of Human Factors research and as systems become more advanced systems, the need for them to be considered does not become less as higher levels of automation are used. Although operators may become less involved in some aspects of the HMT's decision-making, operators will be making decisions in situations which are potentially more safety-critical and with much higher risks. Therefore, it will be necessary that they are supported in making appropriate decisions.

## Appendix A Grounded Theory Literature

Table A.1 - The papers included in the in this review and the themes identified in each of these papers.

Author	Date	Title	Citation	Theme(s) Identified
Ahvenjärvi, S.	2016	The human element and autonomous ships	(Ahvenjärvi, 2016)	Decision Support Systems; Situation Awareness
Barnes, M., Chen, J., Hill, S.	2017	Humans and Autonomy: Implications of Shared Decision-Making for Military Operations	(Barnes et al., 2017a)	Decision Support Systems; Trust; Transparency
Barnes, M., Chen, J., Schaefer, K., E., Giammanco, C., and Hill, S.	2017	Five Requisites for Human-Agent Decision Sharing in Military Environments	(Barnes et al., 2017b)	Decision Support Systems; Trust, Transparency; Teams
Benzmüller, C., and Lomfeld, B.	2020	Reasonable machines: A research manifesto	(Benzmüller and Lomfeld, 2020)	Accountability
Boy, G. A.,	2017	The Handbook of Human-Machine Interaction: A Human-Centered Design Approach	(Boy, 2017)	Trust; Teams; Accountability
Bruemmer, D. J., Marble, J. L., and Dudenhoeffer, D. D.	2002	Mutual initiative in human-machine teams.	(Bruemmer et al., 2002)	Task/Role Allocation; Teams
Chung, Y. H., Yoon, W. C. and Min, D.	2009	A model-based framework for the	(Chung et al., 2009)	Teams

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		analysis of team communication in nuclear power plants		
Cook, M. B., and Smallman H. S.	2013	Human-centered command and control of future autonomous systems	(Cook and Smallman, 2013)	Decision Support Systems
de Laat, P.	2017	Big data and algorithmic decision-making: can transparency restore accountability?	(de Laat, 2017)	Transparency; Accountability
Demir, M. and McNeese, N.	2015	The Role of Recognition Primed Decision Making in Human-Automation (H-A) Teaming	(Demir and McNeese, 2015)	Teams; Situation Awareness
Dreyer L. O., Oltedal, H. A.	2019	Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review	(Dreyer and Oltedal, 2019)	Situation Awareness
Endsley, M. R.	1995	Toward a Theory of Situation Awareness in Dynamic Systems	(Endsley, 1995)	Situation Awareness
Endsley, M. R., and Kaber, D. B.	1999	Level of automation effects on performance, situation awareness and workload in a dynamic control task	(Endsley and Kaber, 1999)	Situation Awareness

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Endsley, M. R., and Kiris, E.	1995	The Out-of-the-Loop Performance Problem and Level of Control in Automation.	(Endsley and Kiris, 1995)	Situation Awareness
Fleischmann, K. R., and Wallace, W. A.	2005	A covenant with transparency: Opening the black box of models	(Fleischmann and Wallace, 2005)	Decision Support Systems; Trust; Transparency
Hoc, J.	2000	From human-machine interaction to human-machine cooperation	(Hoc, 2000)	Trust; Task/Role Allocation
Hoc, J.	2001	Towards a cognitive approach to human-machine cooperation in dynamic situations	(Hoc, 2001)	Trust; Task/Role Allocation
Hoff, K., and Bashir, M.	2015	Trust in Automation: Integrating Empirical Evidence on Factors That Influence Trust.	(Hoff and Bashir, 2015)	Trust; Transparency
Ishowo-Oloko, F., Bonnefon, J., Soroye, Z., Crandall, J., Rahwan, I., and Rahwan, T.	2019	Behavioural evidence for a transparency-efficiency tradeoff in human-machine cooperation	(Ishowo-Oloko et al., 2019)	Transparency
Johnson, M., J., Bradshaw, M., Hoffman, R. R., Feltovich, P. J., and Woods, D. D.	2014	Seven Cardinal Virtues of Human-Machine Teamwork: Examples from the DARPA Robotic Challenge	(Johnson et al., 2014)	Teams

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Karvonen, H., and Martio, J.	2019	Human Factors Issues in Maritime Autonomous Surface Ship Systems Development	(Karvonen and Martio, 2019)	Trust; Task/Role Allocation; Situation Awareness
Knisely, B. M., Joyner, J. S., Rutkowski, A. M., Wong, M., Barksdale, S., Hotham, H., Kharod, K., and Vaughn-Cooke, M.	2020	A cognitive decomposition to empirically study human performance in control room environments	(Knisely et al., 2020)	Decision Support Systems
Lee, J. D., and Moray, N.	1992	Trust, control strategies and allocation of function in human-machine systems	(Lee and Moray, 1992)	Trust
Lee, J. D., and Moray, N.	1994	Trust, self-confidence, and operators' adaptation to automation	(Lee and Moray, 1994)	Trust
Lee, J. D., and See, K. A.,	2004	Trust in Automation: Designing for Appropriate Reliance	(Lee and See, 2004)	Trust
Lemieux, V. L. and Dang, T.	2013	Building accountability for decision-making into cognitive systems	(Lemieux and Dang, 2013)	Decision Support Systems; Accountability
Loh, W., and Loh Sombetzki, J.	2017	Autonomy and responsibility in hybrid systems: The example of autonomous cars.	(Loh and Loh Sombetzki, 2017)	Accountability

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Lyons, J. B., Wynne, K. T., Mahoney, S., and Roebke, M. A.,	2019	Chapter 6 - Trust and Human-Machine Teaming: A Qualitative Study	(Lyons et al., 2019)	Trust; Teams
Mackinnon, S. N., Man, Y., Lundh, M., and Porathe, T.	2015	Command and control of unmanned vessels: Keeping shore based operators in-the-loop	(Mackinnon et al., 2015)	Situation Awareness
Madni, A. M., and Madni, C. C.	2018	Architectural Framework for Exploring Adaptive Human-Machine Teaming Options in Simulated Dynamic Environments	(Madni and Madni, 2018)	Decision Support System; Task/Role Allocation
Mallam, S. C., Nazir, S., and Sharma, A.	2020	The human element in future Maritime Operations – perceived impact of autonomous shipping	(Mallam et al., 2020)	Decision Support System; Trust; Transparency
Matthews, G., Reinerman-Jones, L. E., Barber, D. J., Teo, G., Wohleber, R. W., Lin, J., and Panganiban, A. R.	2016	Resilient autonomous systems: Challenges and solutions	(Matthews et al., 2016)	Trust; Transparency; Teams
Matthews, G., Lin, J., A. R. Panganiban, A. R., and Long, M. D.	2020	Individual Differences in Trust in Autonomous Robots: Implications for Transparency	(Matthews et al., 2020)	Trust; Transparency
McCarthy, J. C., Healey, P. G. T.,	1997	Accountability of work activity in high-	(McCarthy et al., 1997)	Accountability

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Wright, P. C., and Harrison, M. D.		consequence work systems: Human error in context		
McDermott, P. L., Walker, K. E., Dominguez, C. O., Nelson, A., and Kasdaglis, N.	2017	Quenching the thirst for human-machine teaming guidance: Helping military systems acquisition leverage cognitive engineering research	(McDermott et al., 2017)	Trust; Transparency
Miller, C., and Parasuraman, R. 2007	2007	Designing for Flexible Interaction Between Humans and Automation: Delegation Interfaces for Supervisory Control	(Miller and Parasuraman, 2007)	Task/Role Allocation
Millot, P. and Pacaux-Lemoine, M.	2013	A common work space for a mutual enrichment of human-machine cooperation and team-situation awareness	(Millot and Pacaux-Lemoine, 2013)	Trust; Task/Role Allocation; Situation Awareness
Nahavandi, S.	2017	Trusted Autonomy Between Humans and Robots: Toward Human-on-the-Loop in Robotics and Autonomous Systems	(Nahavandi, 2017)	Trust; Transparency
Navarro, J.	2017	Human–Machine interaction theories and lane departure warnings	(Navarro, 2017)	Decision Support System; Trust; Task/Role Allocation

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Neyedli, H., Hollands, J., and Jamieson, G.	2011	Beyond Identity: Incorporating System Reliability Information Into an Automated Combat Identification System	(Neyedli et al., 2011)	Transparency
Oduor, K. F., and Wiebe, E. N.	2008	The Effects of Automated Decision Algorithm Modality and Transparency on Reported Trust and Task Performance	(Oduor and Wiebe, 2008)	Transparency
Panganiban, A. R., Matthews, G., and Long, M. D.	2019	Transparency in Autonomous Teammates: Intention to Support as Teaming Information	(Panganiban et al., 2019)	Decision Support System; Trust; Transparency
Parasuraman, R.	2000	Designing automation for human use: Empirical studies and quantitative models	(Parasuraman, 2000)	Task/Role Allocation
Parasuraman, R., and Manzey, D.	2010	Complacency and Bias in Human Use of Automation: An Attentional Integration	(Parasuraman and Manzey, 2010)	Decision Support System; Trust
Parasuraman, R., and Riley, V.	1997	Humans and Automation: Use, Misuse, Disuse, Abuse	(Parasuraman and Riley, 1997)	Trust; Task/Role Allocation
Parasuraman, R., and Wickens, C. D.	2008	Humans: Still Vital After All These Years of Automation	(Parasuraman and Wickens, 2008)	Task/Role Allocation

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Parasuraman, R. Sheridan, T. B., and Wickens C. D.	2000	A model for types and levels of human interaction with automation	(Parasuraman et al., 2000)	Task/Role Allocation
Parasuraman, R., Barnes, M., Cosenzo, K., and Mulgund, S.	2007	Adaptive Automation for Human-Robot Teaming in Future Command and Control Systems	(Parasuraman et al., 2007)	Task/Role Allocation
Ramos, M., Utne, I., and Mosleh, A.	2019	Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events	(Ramos et al., 2019)	Decision Support System; Situation Awareness
Sadler, G., Battiste, H., Ho, N., Hoffman, L., Johnson, W., Shively, R., Lyons, J., and Smith, D.	2016	Effects of transparency on pilot trust and agreement in the autonomous constrained flight planner	(Sadler et al., 2016)	Trust; Transparency
Schaefer, K. E., Straub, E. R., Chen, J. Y. C., Putney, J. and Evans, A. W.	2017	Communicating intent to develop shared situation awareness and engender trust in human-agent teams	(Schaefer et al., 2017)	Decision Support System; Trust; Teams; Situation Awareness
Seeber, I., Waizenegger, L., Seidel, S., Morana, S., Benbasat, I., and Lowry, P. B.	2019	Collaborating with technology-based autonomous agents: Issues and research opportunities.	(Seeber et al., 2019)	Decision Support System; Transparency; Task/Role Allocation

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Simmler, M., and Frischknecht, R.	2020	A taxonomy of human-machine collaboration: capturing automation and technical autonomy	(Simmler and Frischknecht, 2020)	Task/Role Allocation; Accountability
Smith, P., Geddes, N., Beatty, R. and Hayes, C.	2020	Human-Centered Design of Decision Support Systems	(Smith et al., 2020)	Decision Support Systems
Stensson, P., and Jansson, A.	2014	Autonomous technology - sources of confusion: a model for explanation and prediction of conceptual shifts	(Stensson and Jansson, 2014)	Task/Role Allocation
Taylor, S. M., and De Leeuw, M.	2020	Guidance systems: from autonomous directives to legal sensor-bilities	(Taylor and De Leeuw, 2020)	Decision Support Systems; Accountability
Tulli, S., Correia, F., Mascarenhas, Gomes, S., Melo, F. S., and Paiva, A.	2019	Effects of agents' transparency on teamwork	(Tulli et al., 2019)	Trust; Transparency; Teams
Tossell, C. C., Kim, B., Donadio, B. de Visser, E. J., Holec, R., and Phillips, E.	2020	Appropriately Representing Military Tasks for Human-Machine Teaming Research	(Tossell et al., 2020)	Teams
Vorm, E. S. and Miller, A. D.	2020	Modeling user information needs to enable successful human-machine teams: Designing	(Vorm and Miller, 2020)	Trust; Transparency

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		transparency for autonomous systems		
Voshell, M., Tittle, J., and Roth, E.	2016	Multi-level human-autonomy teams for distributed mission management	(Voshell et al., 2016)	Decision Support System; Task/Role Allocation
Wahlström, M., Hakulinen, J., Karvonen, H., and Lindborg, I.	2015	Human Factors Challenges in Unmanned Ship Operations – Insights from Other Domains	(Wahlström et al., 2015)	Decision Support System; Situation Awareness
Walliser, J. C., de Visser, E. J., Wiese, E. and Shaw, T. H.	2019	Team Structure and Team Building Improve Human–Machine Teaming With Autonomous Agents	(Walliser et al., 2019)	Teams
Warren, A., and Hillas, A.	2020	Friend or frenemy? The role of trust in human-machine teaming and lethal autonomous weapons systems	(Warren and Hillas, 2020)	Trust; Accountability
Westin, C., Borst, C., and Hilbur, B.	2016	Automation Transparency and Personalized Decision Support: Air Traffic Controller Interaction with a Resolution Advisory System	(Westin et al., 2016)	Decision Support System; Transparency
Wickens, C. D.	2008	Situation Awareness: Review of Mica Endsley's 1995 Articles on Situation Awareness	(Wickens, 2008)	Situation Awareness

Appendix A

		Theory and Measurement		
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## Appendix B SAW Taxonomy

### B.1 Schema

Taxonomy subtype	Description
Vicarious past experience	Statements relating to experiencing something in the imagination through the description by another person (e.g., hearing a colleague recall an incident they were involved with) or documentation (e.g., reading about a certain event in an industry magazine or incident/accident report)
Direct past experience	Statements relating to direct personal experience of similar events or situations in the past. This covers events experienced in live, operational contexts as opposed to those experienced through training.
Trained past experience	Statements relating to knowledge developed by direct personal experience of a specific task, event or situation, experienced within the confines of a training scenario (e.g., mariner training, simulator training or training sorties)
Declarative schema	Statements relating to a schema that manifests as a descriptive knowledge of facts, usually as a product of the world information available
Analogical schema	Statements relating to comparisons between things for the purpose of explanation and clarification. Typically these analogies will be structural analogies of physical objects or states of affairs in the world (akin to mental map or mental model)
Insufficient schema	Statements relating to inadequate or lacking knowledge, i.e., a schema is not developed for a certain situation

### B.2 Action

Taxonomy subtype	Description
Operate	Statements relating to direct manipulation (handling) of the MASS controls in order that the MASS can be operated and safety is maintained
Navigate	Statements relating to the process of accurately ascertaining position and planning and following a route or desired course

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Communicate	Statements relating to the sharing or exchange of information
System monitoring	Statements relating to looking at (observing, checking) displays to gain an understanding of the situation
System interaction	Statements relating to the processes of making an input into technological systems in order that the interaction or manipulation has an explicit output
Environment monitoring	Statements relating to observing or checking the internal or external physical environment in order to establish the current state-of-affairs
Concurrent diagnostic action	Statements relating to the process of determining, or attempting to determine, the cause or nature of a problem by examining the available information at the time the incident is occurring
Decision action	Statements relating to a conclusion or resolution that is reached after considering the available information
Situation assessment	Statements relating to actions that relate to the evaluation and interpretation of available information
Non-action	Statements relating to actions that were not performed, either because the situation did not warrant a particular action or because equipment faults did not allow a particular action to be performed or because the pilot made an error or omission.
Standard Operating Procedure	Statements relating to following the prescribed procedure that ought to be routinely followed in a given situation

### **B.3 World**

Taxonomy subtype	Description
Natural environmental conditions	Statements about natural environmental conditions (e.g., weather, light, temperature, noise)
Technological conditions	Statements relating to the state of technological artefacts (e.g., with regards to appearance and working order)

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Communicated information	Statements relating to information available to the operator from other people (e.g., other crew members, VTS, coastguard etc.)
Location	Statements relating to particular places or positions
Artefacts	Statements discussing physical objects, including written information, symbols, diagrams or equipment
Display indications	Statements relating to the information elicited from the physical artefacts
Operational context	Statements relating to the routine functions or activities of the organization (e.g., environmental survey, military training etc.). This can include statements about the importance of being serviceable for the operational context or crew familiarity with the MASS and how this effects decision-making.
MASS status	Statements relating to the current status of the MASS's integrity or performance (e.g., how good or bad it is operating, the current configuration of the MASS, auto-navigation activation etc.)
Severity of problem information	Statements relating to how bad (or otherwise) the critical incident is
Physical cues	Statements relating to external cues that provide information of conditions
Absent information	Statements relating to information that was missing, not present or lacking.

## Appendix C Example interview quotes for the SWARM design and training principles

Design/Training Principle	SAW Code	Freq- uency	Quote
Clear indications of the automation mode, MASS health status, the functioning of individual systems, key MASS parameters and if any sensors are not receiving current data	Display Indications	39	<i>“And the practically, they could also take on the task of looking at the display and seeing if there was, I don't know, the engine has stopped or something like that. And that works okay and then we could You can you can see the the sonar data as it's collected. So the scientists will generally look at that and say, you know, I wasn't expecting this sort of pH. Let's let's you know, point in doing anything with this sort of pH that type of question, but that's nothing to do with the operation that's just looking at the data and real-ish time.” (P1)</i>
Ability to monitor the MASS automated systems to check if the behaviour is as expected	System Monitoring	20	<i>“So obviously the first action will be a understanding their system in their unit that are operating, ensuring its critical systems and components are constantly operational, ensuring that they're actually following a track that they have predefined and there's no deviation from that track without a management to change. Monitoring the comms link and the heartbeat system to check that the link between the MASS and RCC is active” (P9)</i>
Time to get used to the difference in how they are gathering information compared to conventional and this may be different to	Direct/Trained Past Experience	14	<i>“I think a lot of it is the experience of actually being there and operating, but it's knowing what equipment you've got and what the, how that can be used to support the task that you're doing. And then around MASS, it's doing the sort of that training course of how systems work and the um, limitations and benefits you get from working with with systems and how you now you come to rely on</i>

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<p>their heavily learnt schema</p>			<p><i>those systems rather than just using your using your own eyes and looking out of a window and that sort of relying on a camera or a radar or an AIS and relying on those systems to provide you with the full picture because you haven't got your eyes or other senses to actually provide that information, um, first of all.” (P2)</i></p>
<p>Understanding how the environmental conditions will affect the MASS behaviour, whether it is safe to use the automation and continue operating</p>	<p>Natural Environmental Conditions</p>	<p>12</p>	<p><i>“if it's quite heavy sea state and it's near the limits of operation, then it might be causing the vessel to roll quite a lot which might be affecting your swath coverage of what you're picking up on the sea bed. So there's there's, it's making sure of the data you're collecting is meeting the required aim or purpose, I guess.” (P4)</i></p>
<p>Multiple information sources to cross reference the location of the MASS including a graphical representation of where the MASS is on a chart with radar overlays and other relevant overlays to compare with the camera feed</p>	<p>Display Indications</p>	<p>11</p>	<p><i>“Other information I guess that's that's the positioning information so a both a digital readouts of where you are, so your your latitude longitude, you know courses and speeds, but then also very sort of graphical representation of where you are that where is that image, where are you on the on the chart, a radar overlay on that sort of same chart so that you can compare them as well as individual images that sort of combined image to provide that one picture and gives you a sort of a quick and easy way of verifying the information.” (P2)</i></p>
<p>Training on the expected behaviours and limitations of the MASS</p>	<p>Trained Past Experience/ Direct Past Experience</p>	<p>9</p>	<p><i>“I think you do need to understand the behaviour, that's why. For example, the C Cat 3 thats here at the university is there's a safety case is built on having power boat 2 as a minimum, yeah. Other places require not just power boat 2, but they're require further qualifications, so somebody understands just what is involved when you press go. And and you're aware of what it can do and</i></p>

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			<i>why why it would do certain things. And and also it helps you understand what the effects of the environment are. Otherwise it it can there's a risk people treat it as playing computer game and it's not it's not an environment where you can go and play a computer game.” (P3)</i>
Training and experience in using the displayed and communicated information to verify the location of the MASS and location of navigational hazards	Navigate	4	<i>“So yeah, so a GNSS radar then echo sounder, the visual cameras and any other sort of of new novel ways of position fixing that you know they're trying to to to bring in bringing all those together. And. Yeah, I think that that all of that and then sort in terms of collision avoidance, it's using the weather radar IS and camera systems and sort of other um listening into sort of a VHF, if there's a call to port about an entrance, that kind of thing, movements lists. So bringing together all the information on what is happening in the areas around you. I think the example you shown was in Plymouth, so there's a lot of movement, a lot of activity in the South Coast areas with war games and what have you. So do you know what is going on around you? There's a lot of fishing floats, a lot of fishermen. Are you aware of what's going on around you?” (P2)</i>
Early warning communications from the giving the operator time to react or feedback on what the system is planning to do	Communicated Information	2	<i>“And enough enough information that they could see problems emerging early so like early warning, so if there's something in their general area enough fidelity that they can see it incoming with enough time to take corrective action. Not there's a boat coming and you're on a collision course, you have 3-2-1 seconds to act.” (P8)</i>

## Appendix D Example interview quotes for each T-SWARM design and training principle

Design Recommendation	SAW Code	Freq- uency	Quote
Have multiple sub-systems/sensors providing information, including for navigation	Display Indications	27	<i>"You can't totally and utterly rely on it and it's the same as when you're navigating a ship by radar. But the big difference between that is when you're operating by radar, you can look out the window and go does the image I'm seeing on this reflect what I'm seeing out there. You can do that to an extent with the USV cause you do have cameras on it, but your range of visibility is much lower than you are on a on a big bulk carrier. You've only got you're a AIS ranges probably about 6 miles max and your radars about the same. So you do you do fall into these limitations, so you've got to you got a cross reference things. You're checking that is there any AIS target where the radar target is and can I see a light when it comes into range you're trying to, you're trying to figure all these things out. But yeah, mostly you trust it." (P11)</i>
An understanding what differences in the information they have cross-referenced could mean	Situation Assessment	23	<i>"So I until you, that's why these cross referencing so if you can cross reference and they're giving you both the same readout then you can sort of be certainly fairly certain that the system what the system's telling you is true. If it starts to then separate then you need to try and figure out a way of justifying of trying to figure out which one is actually giving you the correct information. But I think you trust it until you don't trust it." (P10)</i>
Train operators in verifying and cross-referencing information	System Monitoring	19	<i>"I think the thing with this is you can never trust it too much because you don't. You're just reading figures on the screen... You always gotta look back into it and make sure it's doing what it's telling you it's doing. So</i>

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			<i>it's just that you can't over rely on one piece of information being correct all the time because everything is as a digital input that can be affected.” (P11)</i>
An understanding what actions they may need to take to diagnose and solve the issue when they recognise a fault	Situation Assessment	15	<i>“But then at that point you're then questioning was that lower reading actually correct or was the higher reading correct see then have to start questioning it and doing some tests to try and make sure the vessel's functioning, how you think it is..” (P10)</i>
Experience operating the MASS where it performs all its required tasks in an operational scenario	Direct Past Experience	14	<i>“Do the second run if it's starting to match up with any information that I've held previously, I'd be gaining good confidence now and probably when it did the next turn and started its third run. I'd probably be happy that it's doing what I what it's supposed to be doing so it's building up confidence over time I suppose in the system.” (P3)</i>
Information on the equipment capabilities and limitations	Artefacts	14	<i>“I think they're gonna want an element of understanding that doesn't mean that they need to understand the ins and outs the system at all. I think they probably do need probably in awareness of factors that influence the behaviour. So, things like your comms systems and I think they need at least an understanding of what differing weather conditions are likely to do to those systems. Um. Likewise, if you're running radar and lidar systems again, it's what different conditions might influence the performance characteristics.” (P3)</i>
Takes into account information from multiple sources when navigating	Navigate	12	<i>“With a MASS system you'd probably have, a AIS on your on your MASS system and you can have that represented, so AIS should give you the course and speed that it's doing so yeah, you could compare the AIS with what other information you're getting back</i>

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			<i>from the vehicle to make sure they're corroborated.” (P6)</i>
Information on the capabilities and limitations of each technological system	Technological Conditions	12	<i>“So because I wasn't there and couldn't feel it, I spent a lot of time not trusting the MASS, chart updates to the position, GPS is a big thing and the connectivity I was always concerned with connectivity that if you had a shadow or you went into a blind spot of a larger structure, you'd lose the connection and that's normal on a small ship, big ship no matter what signal balance, signal skip if you hit you hit an installation and the GPS signals were being bounced, you could be actually closer to it than you actually thought you were, or you could be further away from it and you actually were. So I did not trust at any stage, at anytime of my operation. However, I was saying the exact same thing, for my life at sea, I did not trust any system without a verification in my own head, that it was the correct one and that that was my way of managing safety.” (P9)</i>
Information about how the equipment has been certified and tested and whether it meets existing maritime standards	Artefacts	12	<i>“How is a vessel being trained and is it certified and has it been assured against any particular ...standards for its decision making... officer watches go through four years of training...So there is a recognised training pathway, there's a recognised training pathway in a sense of like machine learning and teaching that system. What it's going to do and analyse the situation is there a recognised system for a decision making sort of system. And is that been recognised by a you know, competent, authority the MCA, Lloyds whoever to say that vessel that system is going to take actions in accordance to the rules and it's been tested through a rigorous profile that we've signed off on...” (P2)</i>
Information on the types of faults that could occur and	Technological Conditions	11	<i>“But it's the information side of things is still a is still kinda getting developed cause it is still in its early stages. I mean, we've had we've had one where the vessel started not been able to follow its route properly</i>

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the potential consequences			<i>but it turned out that the thruster wasn't turning how it should have been.” (P11)</i>
Ensure that operators understand each system’s limitations and capabilities and are aware of how to appropriately rely on those systems	System Monitoring	11	<i>“If you were crossing the Atlantic, you're not gonna see any vessels. You wouldn't just fall asleep and expect it to cross itself, you know, cause it could at any point, fail and start doing its own thing. When it's when everything's working great, it's it's really quite reliable. Like the auto heading and things like that. But you can't you can't over rely on it because it can and it has done its had done some strange things sometimes.” (P11)</i>
Knowledge of their responsibilities when monitoring the systems and when it is or is not appropriate to intervene/take back control	System Monitoring	9	<i>“I wouldn't say I'm relying on the MASS for collision avoidance, but the action of of giving you information about a potential collision, I think should be more prevalent because we all know that people's focus is not 100 percent, 24 hours a day. So just as a backup in case you've not noticed the vessel, even if it's the chances of being a collision are you know, 5% or something, just that sort of indication of here's something over here that maybe you should have a little look at is I think really a huge benefit of the systems but as I say, I wouldn't be fully relying upon it at the moment.” (P10)</i>
Understanding of the capabilities and limitations of the navigation equipment	Navigate	8	<i>“As if it's doing that by radar like you, you wouldn't necessarily pick up things like sailing boats or small wooden fishing boats ... especially because as a computer it can only do like it's gonna follow the rules and do whatever it thinks is the safest course of action... It won't make the assumption of oh that so that's a yacht coming over to have a look at us or someone is just curious or you know or it's fine that they're gonna alter in a minute or whatever.” (P11)</i>
Experience of unexpected	Direct Past Experience	7	<i>“I would say it's not very easy to trust it. I wouldn't say it's unproven to this point, it's passed trials and it's</i>

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behaviours and/or system faults			<p><i>doing everything it's meant to, but it's still they can still do things that are a bit funny or have its own issues. But then again, it's as kind of it's important to understand that's not any different from a normal conventional vessel like a vessel, a normal vessel pilot has auto heading. But just because it has auto heading, I wouldn't trust it to just do it's auto heading.” (P11)</i></p>
An understanding of which systems need to be monitored for different types of system faults	System Monitoring	7	<p><i>“So I suppose you know what one thing might be if it's a pre-planned mission, any kind of severe deviation error from that mission might be the first indicator that indication that there's something wrong, that supervisor needs to investigate. So that that's for the sort of track keeping and navigation or there could be a gap in if there was a gap, the gap was to increase so if the latency or the time between updates was to suddenly increase in a way that wasn't expected...” (P4)</i></p>
Multiple sources of information that can be cross-referenced to check the reliability of the systems	Technological Conditions	7	<p><i>“So you know, if you're trying to if someone was trying to stop you surveying that area, they could just, I suppose, to load the area with full AIS information. Or they could put a disrupting vessel in maybe another MASS that's not got any AIS information coming from it. So if you're relying on that source, then they you wouldn't see it if it wasn't transmitting AIS, which means you'd need some sort of radar.” (P6)</i></p>
Understanding the limitations of the technological systems and being able to evaluate the available information	Situation Assessment	6	<p><i>“... to make assessments like things like when I'm passing a fishing vessel, I mean, their trawls can be two miles astern of them but it all depends on the size of the vessel and type of the vessel and what it's doing and everything. I don't understand how a vessel, I mean, unless it just misses it by miles and miles every time, it keeps it 2 miles CPA or something I don't see how it would be able to understand what that vessel is going to do? ...I could see it coming part of it. But I think it would be more of a look at what we can do rather than like trust it.” (P11)</i></p>

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<p>Experience operating the MASS in different conditions</p>	<p>Direct Past Experience</p>	<p>6</p>	<p><i>"I think the longer you spend with the vessel than the more you would understand it... for example, ...the vessel was operating the more time I spent navigating her the more I kind of know about her quirks in terms of like the the nav equipment just stopped working. If you're on a NE heading because that's what her blind spot is. Those types of things you understand when you've been working with her more."</i> (P7)</p>
<p>Ability to log any faults and receive feedback on the cause of the fault</p>	<p>Technological Conditions</p>	<p>6</p>	<p><i>"Everyone feels very empowered to mention any issue. Any problem we've experienced at all because like I say, it's so new... You're not getting back on a conventional ship where people are going... Who's not done their job? There's no one's getting blamed for anything, cause everyone's learning, everyone's adapting and learning for these new vessels... we're both able to report any problem we find because everyone has a different experience and everyone's got a different thing and everything's logged, so you know it's actually getting listened too and looked into. Which is really, really valuable."</i> (P11)</p>
<p>Backup systems for safety/operation critical systems</p>	<p>Technological Conditions</p>	<p>6</p>	<p><i>"I mean with the MASS system, I guess you could have a highly redundant system that will automatically switch over between one navigational system and another."</i> (P1)</p>
<p>External artefacts (e.g. UAVs charts &amp; support vessels) that could verify the information displayed</p>	<p>Artefacts</p>	<p>6</p>	<p><i>"So in that instance then you really relying on visual information or some sort of mother ship or look out vessel that that's able to see what's going on, you know, have a a real world eyes on type activity or you could use a drone in that area. Which would give you a visual indication of what's going on as well as the onboard, the MASS on board cameras and equipment."</i> (P6)</p>

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Using simple indicators for system status	Display Indications	5	<i>"I think you need you need one [indicator] which so everything you don't worry about it or an amber one and then you obviously have to click on that and you say oh it's my sensor gone or engines died or whatever, whatever it might be" (P1)</i>
Multiple referencing systems providing information	Artefacts	5	<i>"I think it's a great system, I have a lot of I have a lot of doubt in my mind about these systems only because we're reliant so much on the electronics that we have to have more than one referencing and one system of information than you will be used to, so it needs to be more than a conventional type vessel." (P9)</i>
Time after system failures to rebuild the trust in the MASS to complete the operation and an explanation of why it occurred	Direct Past Experience	4	<i>"So if it's loss of trust because the platform failed continuously over a period of time, then again it's about building that trust through Ok, taking it out smaller trials, doing building up okay it is now up to an operational level in building it back up to that aspect." (P6)</i>
The ability to monitor information in real-time or near real-time and ensure that operators are aware of the actions they need to take in the event delayed in transmission or communications failure	System Monitoring	4	<i>"...the ability to monitor stuff in real time or near real time is quite important, because if you were to do a mission which takes I don't know 12 hours, 5 days, whatever it takes, and then you can't assess the successful collection of data or quality of a data until after you've finished. Then you could lose trust quite quickly, whereas if you can monitor it in real time or near real time and have confidence, but it's doing or collecting what you want it to do and that helps build trust in it." (P5)</i>
An indication of how current the information is	Display Indications	3	<i>"Some concept of how old this information is does at least give you an idea of whether it's valid or not and can also be indicative whether and there's an issue even</i>

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<p>being displayed is and a clear indication if there is a communications failure</p>			<p><i>if the system hasn't flagged there's a comms drop or there's a particular issue? Continuous stale information does give an indication that something is necessarily behaving the way you'd expect it to." (P3)</i></p>
<p>Information from additional systems to provide an alternative view</p>	<p>Display Indications</p>	<p>3</p>	<p><i>"I guess if you did have some visual on it, you could see whether it's heading north or east, that would help a lot. You could have a spotter drone, maybe that's providing the plan view of what's going on in real time, you could have that collaborating your information and then you've got the information from the sensor as well." (P6)</i></p>
<p>Give the operators an understanding of how the automated systems work</p>	<p>System Monitoring</p>	<p>3</p>	<p><i>"So there will be higher degrees of autonomy becoming linked with higher degrees of autonomy where some of these functions the decision making is now being taken away from the operator. They are one step removed from the process and machine learning or AI or other algorithm, algorithmic patterns are being used to automate task as well as automate navigation, if you get what I mean. To me, that would cause some distrust, because what that's done is eroded my ability to understand or control decision making or it's eroded my ability to control navigation and it's taken away some of my decision making." (P8)</i></p>
<p>Understanding of the potential negative outcomes of different system faults</p>	<p>Situation Assessment</p>	<p>3</p>	<p><i>"And I think the same sorts of principles apply across onto the MASS kit in terms of... it depends on what an exit outcome is and what the consequences associated with that negative outcome are." (P3)</i></p>
<p>Understands how the system makes navigational decisions and can</p>	<p>Navigate</p>	<p>1</p>	<p><i>"...If it wasn't doing what it's supposed to do and that couldn't be explained then you you'd lose trust in it. So if you set it on a course of East and it constantly keeps veering round to a course of north for for no expected</i></p>

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<p>understand why the system has made a navigational decision</p>			<p><i>reason. Or maybe it's having to put lots and lots of rudder on to maintain its course that might be because it's got weed caught up in it, or the weather conditions are the winds got up... But if you could explain why it's not doing what it's supposed to be doing, you'd have more trust in it, if you know what I mean. But if you can't explain why it's doing what it's doing, then you lose trust straight away.” (P6)</i></p>
<p>Experience for novice operators or operators unfamiliar with the platform, to operate the MASS within line of sight</p>	<p>Direct Past Experience</p>	<p>1</p>	<p><i>“So I found that the days that I operated line of sight. I trusted the vessel a lot more when it came to me operating her in the LOC and knew how should react on that day, I knew. I understood the weather conditions like when we're leaving port okay I know I'm getting set a lot to starboard for example. The current is very strong to starboard today or she's taking a lot of time for her to respond on her main thrusters, but Azipods are working really well. It was like those type of decisions...” (P7)</i></p>
<p>Experience operating MASS including over the horizon operations to get used to the lack of physical cues</p>	<p>Direct Past Experience</p>	<p>1</p>	<p><i>“I've been training [as a mariner] and I've been doing this for like 5 or 6 years and it's very much like that is from day one. We're taught look at the window, look at the window, look at the window and then to not be able to do that.” (P7)</i></p>
<p>Ensure that all control modes are clearly displayed on user interfaces including handheld controllers</p>	<p>Display Indications</p>	<p>1</p>	<p><i>“It is displayed [the hand control mode], I think it's displayed only on the hand control, don't think it's on, it's not there particularly remember it's not a big. The point is it's not a big danger. You're now in raw mode or anything. It's just a little raw bus. So you wouldn't particularly look at it really.” (P1)</i></p>

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Indicators showing the error in the sensor data	Display Indications	1	“...you would probably want some body or some level of automation that is monitoring the positional accuracy versus the planned track and then probably have some level of deviation from that wherever it is, deviation from track or wherever it is the GPS error going beyond a certain threshold that would then flag that to an operator to investigate further...” (P4)
System provides updates on what it is doing and why during an operation	Display Indications	1	“...if you just don't understand why it's doing what it's doing, it may be you get a successful survey, but all the information that you got back from the heading sensors or the speed didn't make any were just gobblygook” (P6)
For collision avoidance systems a clear indication which object is being avoided and an explanation of what its going to do and why	Display Indications	1	“...It comes up and gives you warnings, and so it tells you what the object is the same as what we talked about before, when it highlights something, it'll tell it will highlight that, and then it'll start to give an instruction to within the system. So you can see what it's doing and you can see why you can see kind of why it's done it because you know what object it's trying to avoid...” (P10)
Maintenance logs for the equipment	Artefacts	1	“There's also an element of logging and how many hours have been run? How close are we to maintenance periods? And just being aware, being, or at least being cognizant of of those sorts of of things as you move into bigger, more powered vessels running sort of typical, for example diesel engines. Then you're very much into maintenance cycles of how many hours of things been running, when they need checking and. As you move closer to those deadlines, then you're always going to be a bit more, a bit more worried about your filters and you know your problems. But it's. But they're the same on the more electric powered ones” (P3)

## Appendix E Hierarchical Task Analysis for a MASS conducting an environmental survey

0. Complete an environmental survey of a specified area

1. Execute the survey

Plan 1 – Do 1-7 in order and EXIT.

If the survey needs to be paused then do 8.

When the survey needs to be restarted then do 9 and continue plan 1 from the point it was stopped.

If the survey needs to be adjusted then do 10 and continue plan 1.

1.1. Start the MASS survey

Plan 1.1. – Do 1, then do 2, then do 3 and 4 in any order and if the elapsed time and task state is executing then EXIT.

Else then do 5 and EXIT.

1.1.1. Manoeuvre the MASS to be inside the search region

Plan 1.1.1 – Do 1, then do 2 and 3 as required until the MASS is within the search region

1.1.1.1. Take Manual Control

Plan 1.1.1.1. – Do 1 then do 2.

1.1.1.1.1. Go to the Situational Awareness Screen

1.1.1.1.2. Select the 'Manual Control' button

1.1.1.2. Adjust the MASS's speed

Plan 1.1.2.2. - Do 1 and exit or do 2, then do 3 and exit.

1.1.1.2.1. Click on the up or down arrows under Speed

1.1.1.2.2. Type new speed value into text box

1.1.1.2.3. Click 'Enter'

1.1.1.3. Adjust the MASS's heading

Plan 3.1.2.3. - Do 1 and exit or do 2, then do 3 and exit.

1.1.1.3.1. Click on the up or down arrows under heading

1.1.1.3.2. Type new heading value into text box

1.1.1.3.3. Click 'Enter'

1.1.2. Click 'Start'

1.1.3. Check that the elapsed time has started

1.1.4. Check that the Task executing state is 'Executing'

1.1.5. Abort MASS survey

Plan 1.1.5. – Do 1, then do 2.

1.1.5.1. Go to the 'Situational Awareness' screen

1.1.5.2. Select the 'Abort Survey' button under Activity Summary

1.2. Monitor the MASS transiting to start point

Plan 1.2. – Do 1, 2, and 3 regularly until the start point is reached then EXIT.

If there's a 'transiting to hold point fault' then do 4.

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If the RCC supervisor wants to continue then do 5, then do 6.

If the RCC supervisor does not want to continue do 7 and EXIT.

- 1.2.1. Monitor the MASS's position on the MDA
- 1.2.2. Monitor the MASS's speed on situational awareness screen
- 1.2.3. Monitor screen situational awareness screen for alerts
- 1.2.4. Discuss possible course of action with RCC supervisor
- 1.2.5. Take manual control via the interface
  - Follow Plan 1.1.1.1.
- 1.2.6. Manually transit the MASS to the start point
  - Plan 1.2.6.1 – Do 1 and 2 as required until the start waypoint is reached
    - 1.2.6.1. Adjust the MASS's speed
      - Plan 1.2.6.1.1 - Do 1 or 2, then do 3 and exit.
        - 1.2.6.1.1.1. Click on the up or down arrows under Speed
        - 1.2.6.1.1.2. Type new speed value into text box
        - 1.2.6.1.1.3. Click 'Enter'
      - 1.2.6.1.2. Adjust the MASS's heading
        - Plan 1.2.6.1.2 - Do 1 or 2, then do 3 and exit.
          - 1.2.6.1.2.1. Click on the up or down arrows under heading
          - 1.2.6.1.2.2. Type new speed value into text box
          - 1.2.6.1.2.3. Click 'Enter'
  - 1.2.7. Abort the survey
    - Follow Plan 1.1.5.

### 1.3. Monitor the survey equipment deployment

Plan 1.3. – Do 1 and 3 at the same time, then do 2 and 3 at the same time until the survey equipment is deployed and EXIT.

If there's a 'Hold fault' then do 4. If the RCC supervisor wants to continue then do 5, then do 6. If the RCC supervisor does not want to continue do 7 and EXIT.

If there's a 'Hold not stabilised' then do 4. If the RCC supervisor wants to continue then do 6. If auto mode is available then do 8 and repeat plan 1.3. If the RCC supervisor does not want to continue do 7 and EXIT.

If there's a 'Skip Survey Equipment Activity: Hold not Stable' alert then do 4. If the RCC supervisor wants to continue then do 5, then do 6, then do 8 and EXIT. If the RCC supervisor does not want to continue do 7 and EXIT.

If there is a 'STW too High for winch Deployment/Recovery' or a 'Survey Equipment Speed Constraint Exceeded' or an 'Automated winch in Transition: STW Limit Applies' or a 'MASS Hold: STW too High for automated winch Operation' appears then do 5, then do 9 and repeat 9 until the alert is no longer there and continue with plan 1.3.

If a 'Automated winch Activity Precondition not met' or 'Skip Automated winch activity: Precondition not met' alert appears during Survey Equipment deployment then do 5, then do 15, then do 16, then do 8 and EXIT. If auto mode not available then do 6 and EXIT.

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If a 'Survey Equipment Performance Degraded not Aligned' alert appears then do 14, then do

4. If decision maker decides to abort then do 7, else continue with task.

### 1.3.1. Check that the MASS goes into hold mode

Plan 1.3.1 – Do 1 to 5 in order.

- 1.3.1.1. Go to the Situational Awareness Screen
- 1.3.1.2. Under 'Navigation' check that the MASS is in 'Hold' mode
- 1.3.1.3. Check Status is approaching
- 1.3.1.4. Check Status is stabilising
- 1.3.1.5. Check Status is stable

### 1.3.2. Check the survey equipment's deployment states and modes

Plan 1.3.2 – Do 1 to 7 in order

- 1.3.2.1. Go to the Auxiliary Screen
- 1.3.2.2. Go to the Survey Equipment menu
- 1.3.2.3. Select 'Automated winch group'
- 1.3.2.4. Check that the Automated winch Deployment State is 'Lowering'
- 1.3.2.5. Check that the Survey Equipment mode is 'Standby'
- 1.3.2.6. Check that the Automated winch Deployment State is 'Deployed'
- 1.3.2.7. Check that the Survey Equipment mode is 'Operational'

### 1.3.3. Monitor the situational awareness screen for alerts about the survey equipment deployment

### 1.3.4. Discuss possible course of action with the RCC supervisor

### 1.3.5. Take manual control via the interface

Follow Plan 1.1.1.1.

### 1.3.6. Deploy the survey equipment manually

Plan 1.3.6.1 – Do 1 - 7 in order and exit.

- 1.3.6.1. Go to the Auxiliary Screen
- 1.3.6.2. Go to the Survey Equipment menu
- 1.3.6.3. Select 'Automated winch group'
- 1.3.6.4. Check that the Automated winch Deployment State is 'Lowering'
- 1.3.6.5. Check that the Survey Equipment mode is 'Standby'
- 1.3.6.6. Check that the Automated winch Deployment State is 'Deployed'
- 1.3.6.7. Check that the Survey Equipment mode is 'Operational'

### 1.3.7. Abort the survey

Follow Plan 1.1.5.

### 1.3.8. Put the MASS in auto mode

Plan 1.3.8. – Do 1, then do 2.

- 1.3.8.1. Go to the Situational Awareness Screen
- 1.3.8.2. Select the 'Auto' button

### 1.3.9. Adjust the MASS speed

Follow Plan 1.2.6.1.1.

### 1.3.10. Change the survey equipment mode to operational

Plan 1.3.10. – Do 1, then do 2, then do 3.

- 1.3.10.1. Go to the Auxiliary Screen
- 1.3.10.2. Click on 'Automated winch Group' under the Survey Equipment Menu
- 1.3.10.3. Click on 'Operational' under Survey Equipment mode

### 1.3.11. Reboot the survey equipment server

Plan 1.3.11 – Do 1-3 in order.

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- 1.3.11.1. Go to the Auxiliary screen
  - 1.3.11.2. Go to 'Equipment Power' under the MASS menu
  - 1.3.11.3. Click the 'Reboot' button next to the Survey Equipment server
  - 1.3.12. Check the survey equipment faults
  - 1.3.13. Ask the maintainer to resolve the fault
  - 1.3.14. Check position accuracy on the 'Situational Awareness' screen
  - 1.3.15. Manually transit the MASS to the hold point  
Follow plan 1.2.6
  - 1.3.16. Manually put the MASS into hold  
Plan 1.3.16. – Do 1, then if speed is too high do 2, and then do 3. If speed is not too high then do 3 and EXIT.
    - 1.3.16.1. Check MASS speed
    - 1.3.16.2. Reduce speed through water to required for activity  
Plan 1.3.16.2. – Do 1 or 2 and then do 3
      - 1.3.16.2.1. Click on the down arrows under speed until the speed value reads the required speed
      - 1.3.16.2.2. Type speed value into the speed text box
      - 1.3.16.2.3. Click 'Enter'
    - 1.3.16.3. Click on the 'Hold' button
- 1.4. Monitor the MASS conducting the survey  
Plan 1.4. – Do 1 and 2 at the same time, then do 3 if area no longer needs to be covered and repeat until last waypoint is reached and EXIT.

If a 'Survey Equipment not Powered' or 'Survey Equipment Commands Failed' or a 'Survey Equipment Connection Lost' alert appears then do 5, then do 6, if 'Survey Equipment operational' alert appears continue with Task, if the Survey Equipment still not powered on then do 7, if 'Survey Equipment Operational' alert continue with Task, else do 8, if decision maker decides to abort Task then do 9, else continue with the Task.

If a 'Survey Equipment Not Operational' alert appears then do 6, if that mode does not change to operational then do 12, then do 8 if decision maker decides to abort then do 9, else continue with Task

If a 'Survey Equipment Performance Degraded not Aligned' alert appears then do 10, then do 8. If decision maker decides to abort then do 9 else continue with task.

If a 'Acoustic Interference Warning' alert appears then do 11 and continue with Plan 1.4.

If a 'Survey Equipment in Standby Mode' or 'Survey Equipment in Standby Mode: automated winch not Deployed' or Survey Equipment Degraded' or 'Automated winch fault' alert appears if automated winch is deployed then do 12, if there are any Survey Equipment faults,

then do 8 if decision maker decides to abort then do 9. If there are no faults, then do 7 and continue with Plan 1.4.

1.4.1. Monitor the survey progress

Plan 1.4.1. – Do 1, then do 2, 3, 4, and 5 in any order and repeat plan 1.4.1 until last waypoint is reached and EXIT.

- 1.4.1.1. Go to the situational awareness screen
- 1.4.1.2. Check the activity summary matches the correct task
- 1.4.1.3. Check the MASS speed matches the speed for the current activity
- 1.4.1.4. Check the MASS heading matches the heading for the current activity
- 1.4.1.5. Check the MASS progress to the next waypoint on the mission display area

1.4.2. Manage Survey Equipment Observations

Plan 1.4.6. – Do 1 to 5 in order and repeat plan 1.4.6. until all the unnecessary objects are deleted.

- 1.4.2.1. Go to the Situational awareness screen
- 1.4.2.2. Check the Observations list
- 1.4.2.3. Check the created exclusion zone on the MDA
- 1.4.2.4. Select the relevant observation from the list
- 1.4.2.5. Under delete observations click on the delete button

1.4.3. Skip the next survey line

Plan 1.4.3 – Do 1, then do 2.

- 1.4.3.1. Go to the 'Situational Awareness' screen
- 1.4.3.2. Select the 'Skip activity' button under Activity Summary

1.4.4. Complete the survey in manual control

1.4.4.1. Complete the survey manually

Plan 3.2.6.1 – Do 1 and 2 as required to follow the course on the Task display area until the Survey Equipment recovery waypoint is reached.

1.4.4.1.1. Adjust the MASS's speed

Plan 3.2.6.1.1 - Do 1 or 2, then do 3 and exit.

- 1.4.4.1.1.1. Click on the up or down arrows under Speed
- 1.4.4.1.1.2. Type new speed value into text box
- 1.4.4.1.1.3. Click 'Enter'

1.4.4.1.2. Adjust the MASS's heading

Plan 3.2.6.1.2 - Do 1 or 2, then do 3 and exit.

- 1.4.4.1.2.1. Click on the up or down arrows under heading
- 1.4.4.1.2.2. Type new speed value into text box
- 1.4.4.1.2.3. Click 'Enter'

1.4.5. Take manual control via the interface

Follow Plan 1.1.1.1.

1.4.6. Change Survey Equipment mode to Operational

Follow Plan 1.3.10.

1.4.7. Reboot the survey equipment server

Follow Plan 1.3.11.

1.4.8. Check with the RCC supervisor whether to continue

1.4.9. Abort survey

Follow Plan 1.1.15.

1.4.10. Check position accuracy on the 'Situational Awareness' screen

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- 1.4.11. Turn off the Depth Monitor
  - 1.4.11.1. Go to the Auxiliary screen
  - 1.4.11.2. Go to the MASS menu
  - 1.4.11.3. Go to Equipment power
  - 1.4.11.4. Click off by the depth monitor
- 1.4.12. Check the survey equipment faults

### 1.5. Monitor the survey equipment recovery

Plan 1.5.1 – Do 1 to 7 in order.

If there's a 'Transiting to Hold Point' or Automated winch Activity Precondition not met' or 'Skip Automated winch activity: Precondition not met' alert during transit to hold point for recovery then do 8, then do 9, then do 10 and exit.

If there's a 'Skip Survey Equipment Activity: Hold not Stable' during Survey Equipment recovery alert, then do 11, if Decision maker decides to continue then do 8, then do 16, then do 13 and EXIT. If the decision maker decides to abort then do 12 and exit.

If a 'Automated winch Activity Failed: Automated winch Deployed' or 'Skip Automated winch Activity: Automated winch Activity Failed' or 'Skip Survey Equipment Activity: Automated winch Activity Failed' alert appears then do then do 14, if there are any Survey Equipment faults, then do 11 if decision maker decides to abort then do 12. If there are no faults, then do 15 and continue with plan 1.5.1.

- 1.5.1. Monitor the MASS to Survey Equipment recovery Waypoint
- 1.5.2. Go to the Auxiliary Screen
- 1.5.3. Go to the Survey Equipment menu
- 1.5.4. Select 'Automated winch group'
- 1.5.5. Check that Automated winch Deployment State is 'Raising'
- 1.5.6. Check that the Survey Equipment mode is 'Standby'
- 1.5.7. Check that the Automated winch Deployment State is 'Stowed'
- 1.5.8. Take manual control
  - Follow Plan 1.1.1.1.
- 1.5.9. Manually transit to the hold point
  - Follow plan 1.2.6.
- 1.5.10. Recover the survey equipment manually
  - Plan 1.5.10. – Do 1 to 10 in order.
    - 1.5.10.1. Reduce MASS STW to required activity speed
    - 1.5.10.2. Click on the 'Hold' button
    - 1.5.10.3. Go to the Auxiliary Screen
    - 1.5.10.4. Go to the Survey Equipment menu
    - 1.5.10.5. Select 'Automated winch group'
    - 1.5.10.6. Set Survey Equipment mode to 'Standby'
    - 1.5.10.7. Under Survey Equipment click the 'Recover Survey Equipment' button
    - 1.5.10.8. Check that Automated winch Deployment State is 'Raising'
    - 1.5.10.9. Check that Survey Equipment mode is 'Standby'
    - 1.5.10.10. Check that Automated winch Deployment State is 'Stowed'
- 1.5.11. Check with the RCC supervisor whether to continue

- 1.5.12. Abort survey
  - Follow Plan 1.1.15.
- 1.5.13. Put the MASS in auto
  - Follow Plan 1.3.8.
- 1.5.14. Check the survey equipment for faults
  - Plan 1.5.14 – Do 1, if the status is green exit. If the status is amber or red then do 2 and then do 3 and EXIT.
  - 1.5.14.1. Check survey equipment status
  - 1.5.14.2. Click on survey equipment icon
  - 1.5.14.3. Check the type of fault
- 1.5.15. Reboot the survey equipment server
  - Follow Plan 1.3.11.
  
- 1.6. End the MASS survey
  - Plan do 1.6. – Do 1 to 6 in order and exit.
  - 1.6.1. Monitor the MASS transiting to the endpoint
  - 1.6.2. Take Manual Control
    - Follow Plan 1.1.1.1.
  - 1.6.3. Go to the Auxiliary Screen
  - 1.6.4. Click the End button under Task Control
  - 1.6.5. Click on the confirm button
  - 1.6.6. Check Execution State is 'Completed'
  
- 1.7. Pause the survey
  - Plan 1.7. – Do 1 to 4 in order.
  - 1.7.1. Go to the Auxiliary Screen
  - 1.7.2. Click on the Pause button under Task Control
  - 1.7.3. Check Executing State is Paused
  - 1.7.4. Monitor the MASS until it reaches the hold point
  
- 1.8. Resume the survey
  - Plan 1.8. - Do 1 to 4 in order.
  - 1.8.1. Go to the Auxiliary Screen
  - 1.8.2. Check that the MASS is in state to resume the activity
  - 1.8.3. Click on the Resume button under Task Control
  - 1.8.4. Click the Confirm button on the pop-up
  
- 1.9. Adjust the survey
  - Plan 1.9. – Do 1 to 5, in order. If a transit needs to be added then do 6, if a track needs to be added then do 7, then exit.
  - 1.9.1. Go to the Auxiliary Screen
  - 1.9.2. Go to the Task menu
  - 1.9.3. Select the MASS Task Details Menu
  - 1.9.4. Click on the 'Edit MASS Task' button
  - 1.9.5. Click the Confirm button on the pop-up
  - 1.9.6. Add a Transit to the Task
    - Plan 1.9.6. – Do 1 to 8 in order and exit.
    - 1.9.6.1. Click on the Add Transit Button

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- 1.9.6.2. Select the added activity
- 1.9.6.3. Make the appropriate changes
- 1.9.6.4. Go to the Situational Awareness Screen
- 1.9.6.5. Check the added transit
- 1.9.6.6. Make further changes to the added transit
- 1.9.6.7. Go back to the Auxiliary Screen
- 1.9.6.8. Click the Enter Changes button
- 1.9.7. Add a Track to the Task
  - Plan 1.9.7 – Do 1 to 8, in order and exit.
  - 1.9.7.1. Click on the Add Track Button
  - 1.9.7.2. Select the added activity
  - 1.9.7.3. Make the appropriate changes
  - 1.9.7.4. Go to the Situational Awareness Screen
  - 1.9.7.5. Check the added objects
  - 1.9.7.6. Make further changes to the added activity
  - 1.9.7.7. Go back to the Auxiliary Screen
  - 1.9.7.8. Click the Enter Changes button
- 2. Oversee the navigation
  - Plan 2 – Do 1-3 in any order and repeat until the MASS is recovered.
  - 2.1. Routinely monitor objects
    - Plan 2.1. – Do 1, then 2 and 3 in any order. If there is a collision risk then do 4. Repeat plan until the MASS is recovered.
    - 2.1.1. Go to the Situational Awareness Screen
    - 2.1.2. Monitor objects on the Mission Display Area
      - Plan 2.1.2 – Do 1, then do 2 and repeat until the MASS is recovered.
      - 2.1.2.1. Check for the CPA and TCPA on the MDA for the objects
      - 2.1.2.2. Decide which objects may need further monitoring
    - 2.1.3. Check the Track Table
      - Plan 2.1.3 – Do 1, then do 2, then do 3
      - 2.1.3.1. Check for objects that require collision avoidance against them
      - 2.1.3.2. Check for new objects
      - 2.1.3.3. Check for objects that may need further monitoring
    - 2.1.4. Take avoiding action
      - Plan 2.1.4 – Do 1, then 2, then 3
      - 2.1.4.1. Take Manual Control
        - Plan 2.1.4.1 – Do 1, then do 2
        - 2.1.4.1.1. Go to the Situational Awareness Screen
        - 2.1.4.1.2. Select the 'Manual Control' button
      - 2.1.4.2. Adjust the MASS's course
        - Plan 2.1.4.2 – Do 1 and 2 in any order
        - 2.1.4.2.1. Adjust the MASS's speed to the required for the COLREG manoeuvre
          - 2.1.4.2.1.1. Click on arrows under Speed to adjust speed
          - 2.1.4.2.1.2. Type new speed value into text box
          - 2.1.4.2.1.3. Click 'Enter'

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2.1.4.2.2. Adjust the MASS's heading to the required for the COLREG manoeuvre

2.1.4.2.2.1. Click on arrows under Heading to adjust heading

2.1.4.2.2.2. Type new heading value into text box

2.1.4.2.2.3. Click 'Enter'

2.1.4.3. Make the relevant COLREG sound for the manoeuvre

Plan 2.1.4.3 – Do 1, then do 2, if altering course to port then do 3, if altering course to starboard then do 4, if astern propulsion then do 5, if overtaking to port then do 6, if overtaking to starboard then do 7, if being overtaken then do 8, else do 9.

2.1.4.3.1. Go to the Auxiliary Screen

2.1.4.3.2. Go to the MASS menu and select 'Lights and Sounds'

2.1.4.3.3. Click on the 'Altering course to Port' button

2.1.4.3.4. Click on the 'Altering course to Starboard' button

2.1.4.3.5. Click on the 'Astern propulsion' button

2.1.4.3.6. Click on the 'Overtaking to Port' button

2.1.4.3.7. Click on the 'Overtaking to Starboard' button

2.1.4.3.8. Click on the 'Being Overtaken' button

2.1.4.3.9. Click on the 'Unclear Manoeuvre button'

2.2. Routinely monitor the camera feeds

Plan 2.2, – Do 1 and then do 2;

If there are unmarked hazards do 8

Else do 3, then do 4 until track is located;

if the camera lens is not clean do 5, then do 2;

if the camera lens is wet do 6, then do 2;

if the camera lens keeps getting wet do 7, then do 2;

then exit; else exit. Repeat plan until MASS is recovered.

2.2.1. Go to the Camera Screen

2.2.2. Check each camera feed for navigational hazards not marked on the Task Display Area

2.2.3. Move the camera control to locate the object

2.2.4. Click and drag the slider to zoom in and out

2.2.5. Click on the 'Wash' button

2.2.6. Click on the 'Single Wipe' button

2.2.7. Click on the 'Continuous Wipe' button

2.2.8. Add an exclusion zone

2.3. Routinely check for navigation alerts

Plan 2.3. – Do 1, then 2, then 3 routinely until the MASS is recovered

If 'Search region error' alert appears then do 4, then do 5

If 'Imminent Collision: Basic Stop' alert appears then do 4, then do 6,

If 'No Navigation Solution Available' alert appears then do 4, if possible to achieve next waypoint then do 7, else 8, then do 17

If 'Autonomy Output Inhibited' alert appears then do 4, then do 10

If failure is Task critical then do 28, else do 27.

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If 'No Water Depth Information: Sensor Fault' or 'No Water Depth: Depth Monitor Off' alert appears then do 4, then do 11.

If 'STW Data Unavailable' alert appears then do 4, then do 12, then do 13 and then do 20

If 'E-STOP Requested by Emergency Avoidance' or 'E-STOP triggered' alert when the engines need to be restarted then do 30, then do 31, then do 32

If 'Hold no longer Stabilised' alert appears then do 10, then do 34, if the decision is to continue the Task then do 27, else do 29

If 'Transiting to Hold Point' alert appears then do 4, then do 12, then do 7

If 'Hold Fault' alert appears then do 4, if deploying the automated winch then do 11, if recovering the automated winch then do 13

If 'Collision Risk' alert appears then do 16, if action is needed then do 4 and then do 6

Then do 2,

If 'Missed Waypoint' alert appears then do 4, then do 7, then do 17

If 'Poor MASS Response to Speed Command' alert appears then do 18, then do 19, if speed needs to be adjusted then do 20

If 'MASS not Following Autonomy Speed Commands' or 'Poor MASS Response to Heading Command' or 'Position Error Warning' or 'Heading Error Warning' alert appears then do 10, then do 26

If 'Primary Navigation Data Unavailable' alert appears then do 4, then do 14, if MASS position needs adjusting then do 21

If 'Depth Monitor Data Unavailable' alert appears then do 22, if back up sensor not selected then do 23

If 'Search region Warning' alert appears then do 34, if the MASS will cross the search region area on its current course then do 20, then do 21 in any order so that the MASS does leave the operating area

If 'Search region error' alert appears then do 4, then do 5

If 'Water Depth Below Keel Threshold Breached' alert appears then do 4, then do 11, then 21, then do 35, repeat 11 and 35 until the water depth below threshold is no longer breached

If 'Collision Risk but no Avoidance Activated' or 'COLREGS Avoidance in Progress' or 'No Collision Risk: Avoidance Deactivated' or 'Collision Avoidance requesting speed decrease' alert appears then do 16, if there is a risk of collision and avoiding action is needed then do 4 and then do 6

If 'Depth Monitor Power Up Fail' or 'No Water Depth from Sensor' or 'Water Depth Sensor Bottom Track Lost' alert appears then do 24, if there is a collision risk then do 6, then continue with Task.

If 'Automated winch STW Limit Exceeded' alert appears then do 4, then do 20

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If 'No Water Depth' alert appears then do 4, then do 11

Then repeat 1 and 3 until MASS is recovered.

- 2.3.1. Monitor the Situational Awareness Screen for navigation banner alerts
- 2.3.2. Go to the Alerts Table on the Auxiliary Screen
- 2.3.3. Check the alerts table for navigation alerts
- 2.3.4. Take Manual Control
  - Plan 2.3.4 – Do 1, then do 2
    - 2.3.4.1. Go to the Situational Awareness Screen
    - 2.3.4.2. Select the 'Manual Control' button
- 2.3.5. Navigate the MASS inside the search region
  - Plan 2.3.5 – Do 1, then do 2, then do 3 and 4 in any order repeat until MASS is inside the search region
    - 2.3.5.1. Go to the Situational Awareness Screen
    - 2.3.5.2. Go to the Navigation
    - 2.3.5.3. Adjust MASS speed
      - Plan 2.3.5.3 – Do 1 and exit or do 2, then do 3 and exit.
        - 2.3.5.3.1. Click on arrows under Speed to adjust speed
        - 2.3.5.3.2. Type new speed value into text box
        - 2.3.5.3.3. Click 'Enter'
    - 2.3.5.4. Adjust MASS heading
      - Plan 2.3.5.4 – Do 1 or do 2, then do 3
        - 2.3.5.4.1. Click on arrows under Heading to adjust heading
        - 2.3.5.4.2. Type new heading value into text box
        - 2.3.5.4.3. Click 'Enter'
- 2.3.6. Take appropriate avoiding action
  - Plan 2.4.6 – Do 1, then do 2, if required do 3 and 4 in any order and then do 5
    - 2.3.6.1. Go to the Situational Awareness Screen
    - 2.3.6.2. Go to the Navigation
    - 2.3.6.3. Adjust MASS speed
      - Plan 2.3.5.3 – Do 1 or do 2, then do 3
        - 2.3.6.3.1. Click on arrows under Speed to adjust speed
        - 2.3.6.3.2. Type new speed value into text box
        - 2.3.6.3.3. Click 'Enter'
    - 2.3.6.4. Adjust MASS heading
      - Plan 2.3.6.4 – Do 1 or do 2, then do 3
        - 2.3.6.4.1. Click on arrows under Heading to adjust heading
        - 2.3.6.4.2. Type new heading value into text box
        - 2.3.6.4.3. Click 'Enter'
    - 2.3.6.5. Make the relevant COLREG sound for the manoeuvre
      - Plan 2.3.6.5 – Do 1, then do 2, if altering course to port then do 3, if altering course to starboard then do 4, if astern propulsion then do 5, if overtaking to port then do 6, if overtaking to starboard then do 7, if being overtaken then do 8, else do 9.
        - 2.3.6.5.1. Go to the Auxiliary Screen
        - 2.3.6.5.2. Go to the MASS menu and select 'Lights and Sounds'

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- 2.3.6.5.3. Click on the 'Altering course to Port' button
- 2.3.6.5.4. Click on the 'Altering course to Starboard' button
- 2.3.6.5.5. Click on the 'Astern propulsion' button
- 2.3.6.5.6. Click on the 'Overtaking to Port' button
- 2.3.6.5.7. Click on the 'Overtaking to Starboard' button
- 2.3.6.5.8. Click on the 'Being Overtaken' button
- 2.3.6.5.9. Click on the 'Unclear Manoeuvre button'

### 2.3.7. Achieve Waypoint

Plan 2.3.7 – Do 1, then do 2, if required do 3 and 4 in any order and then do 5

- 2.3.7.1. Go to the Situational Awareness Screen
- 2.3.7.2. Go to the Navigation
- 2.3.7.3. Adjust MASS speed

Plan 2.3.5.3 – Do 1 or do 2 then do 3

- 2.3.7.3.1. Click on arrows under Speed to adjust speed
- 2.3.7.3.2. Type new speed value into text box
- 2.3.7.3.3. Click 'Enter'

- 2.3.7.4. Adjust MASS heading

Plan 2.3.6.4 – Do 1 or do 2 then do 3

- 2.3.7.4.1. Click on arrows under Heading to adjust heading
- 2.3.7.4.2. Type new heading value into text box
- 2.3.7.4.3. Click 'Enter'

### 2.3.8. Skip Waypoint

Plan 2.3.8 – Do 1, then do 2

- 2.3.8.1. Go to the Situational Awareness Screen
- 2.3.8.2. Under activity summary click on the skip waypoint button

### 2.3.9. Navigate the MASS to a safe position

Plan 2.3.9 – Do 1 and 2 in any order until MASS is in a safe position

- 2.3.9.1. Adjust MASS speed

Plan 2.3.9.1 – Do 1 or do 2 then do 3

- 2.3.9.1.1. Click on arrows under Speed to adjust speed
- 2.3.9.1.2. Type new speed value into text box
- 2.3.9.1.3. Click 'Enter'

- 2.3.9.2. Adjust MASS heading

Plan 2.3.9.2 – Do 1 or do 2 then do 3

- 2.3.9.2.1. Click on arrows under Heading to adjust heading
- 2.3.9.2.2. Type new heading value into text box
- 2.3.9.2.3. Click 'Enter'

### 2.3.10. Check for failures

Plan 2.3.10 – Do 1, then do 2 if the health status is green then exit, if the health status is orange or red then do 3, then do 4 if there is a relevant fault then do 5, then repeat until all relevant faults have been checked then exit.

- 2.3.10.1. Go to the Auxiliary Screen
- 2.3.10.2. Check the MASS Health status
- 2.3.10.3. Select Health from the Health & Usage Menu
- 2.3.10.4. Check the fault list for relevant faults
- 2.3.10.5. Select the fault from the fault list

### 2.3.11. Check water depth on naval chart

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### 2.3.12. Check tidal current

Plan 2.3.12 – Do 1, then do 2 and 3 in any order

- 2.3.12.1. Go to MASS Navigational Data on the Situational Awareness Screen
- 2.3.12.2. Check set
- 2.3.12.3. Check drift

### 2.3.13. Check Speed over ground

Plan 2.3.13 – Do 1, then do 2

- 2.3.13.1. Go to MASS Navigational Data on the Situational Awareness Screen
- 2.3.13.2. Check the Speed Over Ground

### 2.3.14. Check position of the MASS using cameras

Plan 2.3.14 – Do 1, then do 2

- 2.3.14.1. Go to the Camera Screen
- 2.3.14.2. Use the cameras to check the distance from the MASS to other objects and objects

### 2.3.15. Re-engage Hold

Plan 2.3.15 – Do 1, then do 2

- 2.3.15.1. Go to MASS Navigation on the Situational Awareness Screen
- 2.3.15.2. Click on the hold button

### 2.3.16. Monitor the MASS's position to nearby vessels

### 2.3.17. Put MASS in auto mode

Plan 2.3.17 – Do 1, then do 2

- 2.3.17.1. Go to MASS Navigation on the Situational Awareness Screen
- 2.3.17.2. Click on the Auto button

### 2.3.18. Monitor the MASS's Speed Through Water

Plan 2.3.18 – Do 1, then do 2

- 2.3.18.1. Routinely go to MASS Navigational Data on the Situational Awareness Screen
- 2.3.18.2. Check Speed Through Water

### 2.3.19. Check the MASS's Speed Sensors

Plan 2.3.19 – Do 1, then do 2, then do 3 if the speed sensor is not available or there are any warnings then do 36

- 2.3.19.1. Go to the Auxiliary screen
- 2.3.19.2. Select 'Nav sensors' from the 'Navigation & SA' menu
- 2.3.19.3. Check for any speed sensor warnings and the sensor is available

### 2.3.20. Adjust MASS speed

Plan 2.3.20 – Do 1 or do 2 then do 3

- 2.3.20.1. Click on arrows under Speed to adjust speed
- 2.3.20.2. Type new speed value into text box
- 2.3.20.3. Click 'Enter'

### 2.3.21. Adjust MASS heading

Plan 2.3.21 – Do 1 or do 2 then do 3

- 2.3.21.1. Click on arrows under Heading to adjust heading
- 2.3.21.2. Type new heading value into text box
- 2.3.21.3. Click 'Enter'

### 2.3.22. Check that the backup sensor has been selected

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Plan 2.3.22 – Do 1, then do 2, then do 3, if the back up sensor is not selected then do 23, else exit.

- 2.3.22.1. Go to the Auxiliary screen
- 2.3.22.2. Select 'Nav sensors' from the 'Navigation & SA' menu
- 2.3.22.3. Check the backup sensor toggle is on

2.3.23. Select the backup sensor manually

Plan 2.3.23 – Do 1, then do 2, then do 3,

- 2.3.23.1. Go to the Auxiliary screen
- 2.3.23.2. Select 'Nav sensors' from the 'Navigation & SA' menu
- 2.3.23.3. Switch the toggle button to on for the backup sensor

2.3.24. Monitor other vessels

Plan 2.3.24 – Do 1, then do 2

- 2.3.24.1. Go to the Situational Awareness Screen
- 2.3.24.2. Monitor the other vessel's track on the PDA

2.3.25. Perform collision avoidance manoeuvres

Plan 2.3.25 – Do 1 or 2 as needed

2.3.25.1. Adjust MASS speed

Plan 2.3.25.1 – Do 1 or do 2 then do 3

- 2.3.25.1.1. Click on arrows under Speed to adjust speed
- 2.3.25.1.2. Type new speed value into text box
- 2.3.25.1.3. Click 'Enter'

2.3.25.2. Adjust MASS heading

Plan 2.3.25.2 – Do 1 or do 2 then do 3

- 2.3.25.2.1. Click on arrows under Heading to adjust heading
- 2.3.25.2.2. Type new heading value into text box
- 2.3.25.2.3. Click 'Enter'

2.3.26. Continue the Task in Manual Control

Plan 2.3.26 – Do 1, then do 2, then do 3 until the Task steps are complete.

- 2.3.26.1. Go to the Situational Awareness Screen
- 2.3.26.2. Select the 'Manual Control' button
- 2.3.26.3. Carry out the remaining activity steps in Manual Control

2.3.27. Abort the survey

Plan 2.3.27. – Do 1, then do 2, then do 3

- 2.3.27.1. Go to the Situational Awareness Screen
- 2.3.27.2. Click on Abort Survey in the Activity Summary
- 2.3.27.3. Click the confirm button in the pop-up

2.3.28. Abort the Task to end

Plan 2.3.28. – Do 1, then do 2, then do 3

- 2.3.28.1. Go to the Auxiliary Screen
- 2.3.28.2. Click on Abort to under Task Control
- 2.3.28.3. Click on Abort to End

2.3.29. Navigate the MASS in Manual Control to the recovery point

Plan 2.3.29. – Do 1 and 2 in any order and repeat until the recovery point is reached

2.3.29.1. Adjust MASS speed

- 2.3.29.1.1. Click on arrows under Speed to adjust speed
- 2.3.29.1.2. Type new speed value into text box

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- 2.3.29.1.3. Click 'Enter'
- 2.3.29.2. Adjust MASS heading
  - 2.3.29.2.1. Click on arrows under Heading to adjust heading
  - 2.3.29.2.2. Type new heading value into text box
  - 2.3.29.2.3. Click 'Enter'
- 2.3.30. Clear the E-Stop on the RCC Handheld controller
- 2.3.31. Restart the MASS's Engines on the RCC Handheld controller
- 2.3.32. Restart the MASS Task

Plan 2.3.32 – Do 1, then do 2, then do 3.

- 2.3.32.1. Go to Task Control on the 'Auxiliary screen'
- 2.3.32.2. Click on 'End'
- 2.3.32.3. Click 'Confirm' in the pop-up window
- 2.3.33. Discuss plan with the RCC supervisor and Maintainer
- 2.3.34. Monitor the MASS's position
  - Plan 2.3.34 – Do 1, then do 2 repeat until the situation is resolved
    - 2.3.34.1. Routinely go to MASS Navigational Data on the Situational Awareness Screen
    - 2.3.34.2. Check the MASS's position
  - 2.3.35. Check the MASS's water depth below keel
    - Plan 2.3.35. – Do 1, then do 2 repeat until the situation is resolved
      - 2.3.35.1. Routinely go to MASS Navigational Data on the Situational Awareness Screen
      - 2.3.35.2. Check the Water Depth

### 3. Monitor the MASS system alerts

Plan Do 1 and 2 routinely until the MASS is recovered

If a 'Flood Detected' alert appears then do 3.

If a 'Fire Detected' alert appears then do 4.

If a 'Climate Control Failure' or a 'Fire Detection System Fault' or a 'Bilge Pump Fault' or a 'Lidar and Radar Faulted' or a 'Horn fault' or a 'On board Microphone Fault' or a 'Fuel monitoring fault' or a 'Hydraulic system fault' or a 'Data store fault' or a 'Data store not available' alert appears then do 5.

If a 'Fire Detection System Degraded' or a 'Climate Control Degraded' or a 'Navigation Light Fault' or a 'Infrared camera Fault' or a 'Camera fault' or a 'Lidar fault' or a 'Radar failed' or a 'Radar degraded' or a 'Generator warning' or a 'Charger/Inverter degraded' or a 'Hydraulic system warning' alert appears then do 6.

If a 'Fuel nearly empty' alert appears then do 7.

If an 'Insufficient Fuel to reach waypoint' alert appears then do 8.

If a 'Steering fault' alert appears then do 9.

If an 'AIS transmission fault' occurs do 10.

If a 'Sea State Unavailable (warning)' or a 'Air Temp, Pressure or Humidity Unavailable' or a 'Wind Data Unavailable' alert appears then do 11.

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- 3.1. Monitor the Situational Awareness screen for alert banners
- 3.2. Monitor the alerts table
- 3.3. Respond to a flood in a compartment  
Plan 3.3. – Do 1-4 in order then if ‘flood alarm cleared’ is not displayed repeat plan 3.3. until ‘flood alarm cleared’ is displayed.
  - 3.3.1. Go to auxiliary screen
  - 3.3.2. Select ‘Activate’ for the bilge pump for that compartment
  - 3.3.3. Monitor bilge pump timer
  - 3.3.4. Check for ‘flood alarm cleared’
- 3.4. Respond to fire on board  
Plan 3.4. – Do 1 if system not already on then do 2 else EXIT.
  - 3.4.1. Check the automatic fire suppression system is switched on
  - 3.4.2. Turn the fire suppression system on manually
- 3.5. Respond to major system fault  
Plan 3.5. – Do 1, then 2, if the RCC supervisor decides to continue EXIT and continue else do 3, 4 and 5 in order.
  - 3.5.1. Tell the RCC supervisor so they can decide a course of action
  - 3.5.2. Check for specific faults
    - 3.5.2.1. Go to the Auxiliary Screen
    - 3.5.2.2. Check the MASS Health status at the top of the screen
    - 3.5.2.3. Select Health from the Health & Usage Menu
    - 3.5.2.4. Check the fault list for relevant faults
    - 3.5.2.5. Select the fault from the fault list
    - 3.5.2.6. Update the RCC supervisor on the fault
  - 3.5.3. Abort survey to end  
Follow Plan 1.1.15.
  - 3.5.4. Contact support vessel to go and recover the MASS
  - 3.5.5. Manually transit the MASS to the recovery point  
Plan 3.5.4. - Do 1 then 2, then 3 and 4 in any order and repeat until the recovery point is reached
    - 3.5.5.1. Go to the Situational Awareness Screen
    - 3.5.5.2. Select the ‘Manual Control’ button
    - 3.5.5.3. Adjust MASS speed
      - 3.5.5.3.1. Click on arrows under Speed to adjust speed
      - 3.5.5.3.2. Type new speed value into text box
      - 3.5.5.3.3. Click ‘Enter’
    - 3.5.5.4. Adjust MASS heading
      - 3.5.5.4.1. Click on arrows under Heading to adjust heading
      - 3.5.5.4.2. Type new heading value into text box
      - 3.5.5.4.3. Click ‘Enter’
- 3.6. Respond to minor system fault  
Plan 3.6. – Do 1, then 2, if the RCC supervisor decides to continue EXIT and continue else do 3 and 4.
  - 3.6.1. Tell the RCC supervisor so they can decide a course of action
  - 3.6.2. Check for specific faults
    - 3.6.2.1. Go to the Auxiliary Screen
    - 3.6.2.2. Check the MASS Health status at the top of the screen
    - 3.6.2.3. Select Health from the Health & Usage Menu
    - 3.6.2.4. Check the fault list for relevant faults

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- 3.6.2.5. Select the fault from the fault list
- 3.6.2.6. Update the RCC supervisor on the fault
- 3.6.3. Abort survey to end  
Follow Plan 1.1.15.
- 3.6.4. Manually transit the MASS to the recovery point  
Do 1 then 2, then 3 and 4 in any order and repeat until the recovery point is reached
  - 3.6.4.1. Go to the Situational Awareness Screen
  - 3.6.4.2. Select the 'Manual Control' button
  - 3.6.4.3. Adjust MASS speed
    - 3.6.4.3.1. Click on arrows under Speed to adjust speed
    - 3.6.4.3.2. Type new speed value into text box
    - 3.6.4.3.3. Click 'Enter'
  - 3.6.4.4. Adjust MASS heading
    - 3.6.4.4.1. Click on arrows under Heading to adjust heading
    - 3.6.4.4.2. Type new heading value into text box
    - 3.6.4.4.3. Click 'Enter'
- 3.7. Respond to fuel warning  
Plan 3.7. – Do 1, then if the RCC decides to continue with the survey EXIT else do 2 and 3.
  - 3.7.1. Notify the RCC supervisor of the fuel warning
  - 3.7.2. Abort survey to end  
Follow Plan 1.1.15.
  - 3.7.3. Manually transit the MASS to the recovery point  
Do 1 then 2, then 3 and 4 in any order and repeat until the recovery point is reached
    - 3.7.3.1. Go to the Situational Awareness Screen
    - 3.7.3.2. Select the 'Manual Control' button
    - 3.7.3.3. Adjust MASS speed
      - 3.7.3.3.1. Click on arrows under Speed to adjust speed
      - 3.7.3.3.2. Type new speed value into text box
      - 3.7.3.3.3. Click 'Enter'
    - 3.7.3.4. Adjust MASS heading
      - 3.7.3.4.1. Click on arrows under Heading to adjust heading
      - 3.7.3.4.2. Type new heading value into text box
      - 3.7.3.4.3. Click 'Enter'
- 3.8. Respond to MASS running out of fuel  
Plan 3.8. – Do 1-4 in order.
  - 3.8.1. Notify the RCC supervisor the MASS has run out of fuel
  - 3.8.2. Navigate the MASS to a safe position with the remaining fuel
  - 3.8.3. Drop the anchor
    - 3.8.3.1. Go to the Situational Awareness screen
    - 3.8.3.2. Select drop anchor
  - 3.8.4. Contact support vessel to go and recover the MASS
- 3.9. Handle a steering fault  
Plan 3.9. – Do 1 -3 in order, if the MASS fails to perform a stop then do 4.
  - 3.9.1. Monitor the USV performs a stop
  - 3.9.2. Tell the RCC supervisor there is a steering fault
  - 3.9.3. Contact the support vessel to recover the MASS
  - 3.9.4. Select the emergency stop button
- 3.10. Notify the RCC supervisor that an 'AIS transmission fault' alert has occurred
- 3.11. Respond to environment sensor warnings
  - 3.11.1. Notify the RCC supervisor of the warning
  - 3.11.2. Ask the RCC supervisor for an estimate of the conditions

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- 3.11.3. Discuss an appropriate course of action
- 3.11.4. Abort survey to end  
Follow Plan 1.1.15.
- 3.11.5. Manually transit the MASS to the recovery point  
Do 1 then 2, then 3 and 4 in any order and repeat until the recovery point is reached
  - 3.11.5.1. Go to the Situational Awareness Screen
  - 3.11.5.2. Select the 'Manual Control' button
  - 3.11.5.3. Adjust MASS speed
    - 3.11.5.3.1. Click on arrows under Speed to adjust speed
    - 3.11.5.3.2. Type new speed value into text box
    - 3.11.5.3.3. Click 'Enter'
  - 3.11.5.4. Adjust MASS heading
    - 3.11.5.4.1. Click on arrows under Heading to adjust heading
    - 3.11.5.4.2. Type new heading value into text box
    - 3.11.5.4.3. Click 'Enter'

## Appendix F Behavioural Markers System

### F.1 Closed-Loop Communication:

Exchanging task-relevant information with other team members and ensuring information has been received and understood (Salas et al., 2005).

#### F.1.1 Exchanging information

Providing appropriate information to others and being receptive to information provided.

#### F.1.2 Human-Human:

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Communicates in a clear and open/candid manner</li> <li>The amount of communication is appropriate for the situation</li> <li>Uses language appropriately, e.g., clear phrasing, terminology and speed of delivery</li> <li>Addresses appropriate team members (e.g., those engaged in task)</li> <li>Considers and shares intent prior to undertaking decision or action</li> <li>Listens to relevant information being given by other team members and takes it into account when making a decision or taking action</li> <li>Acknowledges that they have received the information</li> <li>Requests relevant information from the appropriate source/s</li> <li>Promptly warns others of cues suggesting potential hazards</li> <li>Uses the right medium to deliver the message (face-to-face, radio, email, telephone etc.)</li> </ul>	<ul style="list-style-type: none"> <li>Does not share information with other team members or their communication is unclear</li> <li>Provides too much, too little or vague communication</li> <li>Uses language inappropriately, e.g., unclear phrasing, incorrect terminology</li> <li>Fails to identify the correct team member for communication</li> <li>Continues with verbal communication where unsuitable (e.g. interrupts busy team member/s with inappropriate request)</li> <li>Ignores relevant information been given to them by another team member or fails to take the information into consideration when making a decision or taking an action</li> <li>Does not acknowledge they have received the information</li> <li>Requests irrelevant, or fails to ask for relevant, information from appropriate source/s</li> <li>Fails to warn team members about a potential hazard</li> <li>Uses an inappropriate medium to deliver a message</li> </ul>

#### F.1.3 Human-Machine:

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Accepts relevant information from the system and uses that information when taking an action</li> <li>Acknowledges and responds to communications, feedback and warnings from the automated systems where necessary (e.g.,</li> </ul>	<ul style="list-style-type: none"> <li>Fails to use information from the system when taking action</li> <li>Ignores or does not respond adequately to communications, feedback and warnings from the automated systems</li> <li>Requests irrelevant, or fails to ask for relevant, information from appropriate source/s</li> </ul>

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<p>responds to take over requests from the system)</p> <ul style="list-style-type: none"> <li>• Requests relevant information from the appropriate source/s</li> <li>• Provides the necessary information to the machine teammate in a timely manner (e.g., adds in a navigational hazard not marked on the electronic chart so that the navigation system has time to replan the route)</li> </ul>	<ul style="list-style-type: none"> <li>• Does not check that instructions or requests given have been received and successfully performed</li> <li>• Fails to provide the machine teammate with information or provides that information to them too late.</li> </ul>
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### F.1.4 Machine-Human:

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Communicates in a clear and open/candid manner</li> <li>• The amount of communication is appropriate for the situation</li> <li>• Uses language appropriately, e.g., clear phrasing, terminology and speed of delivery</li> <li>• Addresses appropriate team members (e.g., those engaged in task)</li> <li>• Considers and shares intent prior to undertaking decision or action</li> <li>• Accepts relevant information from human team members and uses that information when taking an action</li> <li>• Acknowledges that they have received the information</li> <li>• Requests relevant information from the appropriate source/s</li> <li>• Promptly warns others of cues suggesting potential hazards</li> <li>• Uses the right medium to deliver the message (visual, auditory, haptic etc.) and the type of message</li> </ul>	<ul style="list-style-type: none"> <li>• Does not share information with other team members or their communication is unclear</li> <li>• Provides too much, too little or vague communication</li> <li>• Uses language inappropriately, e.g., unclear phrasing, incorrect terminology</li> <li>• Fails to identify the correct team member for communication</li> <li>• Continues with verbal communication where unsuitable (e.g. interrupts busy team member/s with inappropriate request)</li> <li>• Ignores relevant information been given to the system by a human team member or fails to take the information into consideration when making a decision or taking an action</li> <li>• Does not acknowledge they have received the information</li> <li>• Requests irrelevant, or fails to ask for relevant, information from appropriate source/s</li> <li>• Fails to warn team members about a potential hazard</li> <li>• Uses an inappropriate medium to deliver a message or the wrong type of message</li> </ul>

### F.1.5 Giving instructions

Being clear and concise when requesting action from another team member.

### F.1.6 Human-Human:

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Explains in sufficient detail what is required or expected</li> <li>• Seeks to ensure relevant team members are aware of new instruction(s)</li> <li>• Asks questions and observes others to confirm their understanding</li> <li>• Updates instructions as task/situation progresses</li> </ul>	<ul style="list-style-type: none"> <li>• Provides unclear or inconsistent information about requirements or task information</li> <li>• Proceeds with following new instruction without informing team of action</li> <li>• Does not check whether plans and expectations have been understood</li> <li>• Provides instruction but does not update as task/situation progresses</li> </ul>

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**F.1.7 Human-Machine:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Ensures that the provide all the information required for the system to perform a task</li> <li>• Ensures that any instructions or requests given to the automated systems have been successfully received and performed by the automated system</li> <li>• Updates instructions as task/situation progresses</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to provide the machine teammate with information or provides that information to them too late.</li> <li>• Ignores or does not respond adequately to communications, feedback and warnings from the automated systems</li> <li>• Does not check that instructions or requests given have been received and successfully performed</li> </ul>

**11.5.1 Machine-Human:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Explains in sufficient detail what is required or expected</li> <li>• Seeks to ensure relevant team members are aware of new instruction(s)</li> <li>• Provides feedback to their human team members that their request has been received/executed or if not why the system was unable to complete the request</li> <li>• Updates instructions as task/situation progresses</li> </ul>	<ul style="list-style-type: none"> <li>• Provides unclear or inconsistent information about requirements or task information</li> <li>• Proceeds with following new instruction without informing team of action</li> <li>• Does not provide feedback that a request has been received/executed or why it was unable to</li> <li>• Provides instruction but does not update as task/situation progresses</li> </ul>

**F.1.8 Providing feedback to other team members**

Providing an opportunity to raise questions and seeking to address any misunderstandings in communication.

**F.1.9 Human-Human:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Responds to briefs and indicates they have been understood</li> <li>• Regularly raises opportunity for questions and takes the time to respond to the questions asked</li> <li>• Actively seeks and acts upon feedback</li> <li>• Receives feedback constructively</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to acknowledge or respond to brief or instructions</li> <li>• Acknowledges brief but carries out different task/ action</li> <li>• Responds negatively to questions and discourages other team members from speaking up</li> <li>• Reacts defensively or aggressively to feedback</li> </ul>

**F.1.10 Human-Machine:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Acknowledges they have received warnings, notifications or other feedback from the system</li> </ul>	<ul style="list-style-type: none"> <li>Fails to acknowledge or respond to warnings, notifications and other system feedback</li> </ul>

**F.1.11 Machine-Human:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Asks human team members for feedback and acts upon the feedback when appropriate</li> </ul>	<ul style="list-style-type: none"> <li>Does not ask for any feedback or take the feedback into consideration</li> </ul>

**F.2 Decision-making****F.2.1 Rules and procedures decision-making:**

Ensuring that decisions are in line with the appropriate regulations and procedures when appropriate.

**F.2.2 Selecting and following regulations and procedures****F.2.3 Human-Human/Human-Machine:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Demonstrates that they can select and follow the appropriate regulations, standard and emergency operating procedures.</li> <li>Understands when they may need to deviate from their standard operating procedures</li> </ul>	<ul style="list-style-type: none"> <li>Selects the wrong regulations or procedures to follow in the situation.</li> <li>Does not follow the standard/emergency operating procedure correctly (assuming the situation is appropriate for a standard or emergency operating procedure)</li> <li>Follows a standard operating procedure in a situation where a standard operating procedure is not appropriate</li> </ul>

**F.2.4 Machine-Human:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Demonstrates that they can select and follow the appropriate regulations, standard and emergency operating procedures.</li> </ul>	<ul style="list-style-type: none"> <li>Selects the wrong regulations or procedures to follow in the situation.</li> <li>Does not follow the standard/emergency operating procedure correctly (assuming the situation is appropriate for a standard or emergency operating procedure)</li> </ul>

**F.2.5 Analytical Decision-making**

Weighing up alternatives and selecting approach to task in consideration of relative risk and confirming input of, and acceptance by, other team members.

**F.2.6 Identifying and selecting options**

Weighing up multiple options and settling on appropriate option.

**F.2.7 Human-Human/Human-Machine:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Considers appropriate response to situation and alternative solutions</li> <li>• Discounts inappropriate options</li> <li>• Demonstrates appropriate response to mitigate risk</li> <li>• Seeks to contribute to decision-making with other team members</li> <li>• Encourages idea generation and challenges existing norms</li> <li>• Ensures agreement on appropriate course of action</li> <li>• Consult those with specialist expertise or local knowledge when required</li> </ul>	<ul style="list-style-type: none"> <li>• Moves forward with task before considering additional options</li> <li>• Selects or fails to recognise inappropriate options</li> <li>• Proceeds with potentially risky course of action (e.g., heading into poor weather)</li> <li>• Shows reluctance to contribute to group decision-making</li> <li>• Proceeds without agreement of other team members</li> <li>• Makes decisions without recognising or acknowledging own limitations or lack of experience</li> </ul>

**F.2.8 Machine-Human:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Considers appropriate response to situation and alternative solutions</li> <li>• Demonstrates appropriate response to mitigate risk</li> <li>• Seeks to contribute to decision-making with other team members (e.g. offers advice or suggestions)</li> <li>• Ensures agreement on appropriate course of action</li> </ul>	<ul style="list-style-type: none"> <li>• Moves forward with task before considering additional options</li> <li>• Proceeds with potentially risky course of action (e.g., heading into poor weather)</li> <li>• Does not have the ability to offer advice or suggestions to contribute to ground decision-making</li> <li>• Does not offer the operator a chance to agree on the course of action</li> </ul>

**F.2.9 Reviewing course of action**

Revisiting and assessing the outcomes of the decision made

**F.2.10 Human-Human/Machine-Human:**

Positive behavioural markers	Negative behavioural markers

<ul style="list-style-type: none"> <li>• Confirms with other team members what has happened and whether it has met decision goal</li> <li>• Identifies if anything has been missed by selecting option</li> <li>• Decides on further action if necessary</li> </ul>	<ul style="list-style-type: none"> <li>• Shows unwillingness to revisit decision</li> <li>• Does not communicate what has happened based on decision</li> <li>• Continues without assessment of further action</li> </ul>
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**F.2.11 Human-Machine:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Checks their interface to confirm what has happened and whether it has met the decision goal</li> <li>• Identifies if anything has been missed by selecting option</li> <li>• Decides on further action if necessary</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to check their interface to confirm that the decision goal has been met</li> <li>• Does not communicate what has happened based on decision</li> <li>• Continues without assessment of further action</li> </ul>

**F.2.12 Naturalistic Decision-making**

**F.2.13 Recognition primed decision-making**

Using experience and intuition to make decisions.

**F.2.14 Human-Human/Human-Machine:**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Making quick decisions based upon prior experience and intuition.</li> </ul>	<ul style="list-style-type: none"> <li>• Makes quick but inappropriate decisions for the situation.</li> </ul>

**F.3 Leadership**

Ability to direct and coordinate the activities of other team members, assess team performance, assign tasks, develop team knowledge, skills, and abilities, motivate team members, plan and organize, and establish a positive atmosphere (Salas et al., 2005).

**F.3.1 Setting and maintaining team atmosphere**

Setting the tone for an effective team environment.

**F.3.2 Human-Human**

Positive behavioural markers	Negative behavioural markers
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## Appendix F

<ul style="list-style-type: none"> <li>• Seeks to identify and resolve conflict within the team</li> <li>• Modifies behaviours and actions to take into account current emotions and state of team (e.g. uses humour to diffuse tense situations)</li> <li>• Treats all team members with respect and to the same standard</li> <li>• Uses reasoning and diplomacy when interacting with other team members and external agencies (e.g., other vessels or VTS)</li> <li>• Recognises, appreciates and supports others' contributions</li> <li>• Creates a culture that enables challenge and participation while maintaining command authority</li> <li>• Creates a safe and trusting environment for team members, supporting them to openly share lack of knowledge and to speak up without hesitation</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to identify and address factors underlying conflict</li> <li>• Behaves in a manner that invites conflict such as using sarcasm, being abrupt or overly dismissive of others</li> <li>• Sets inappropriate tone (e.g. shuts down other team members, becomes overbearing/ commanding, creates hostile atmosphere)</li> <li>• Shows signs of distress (e.g. raises voice) when interacting with team or external agencies</li> <li>• Avoids getting involved or helping to resolve conflict even when aware of correct course of action (e.g. fails to emphasise priority of task when necessary)</li> <li>• Acts as a source of conflict within the team (e.g. argumentative, encourages separation between flight team and technical team)</li> </ul>
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### F.3.3 Co-ordinating activities

Taking oversight of an operation, action/series of actions, and ensuring teamwork effectiveness.

### F.3.4 Human-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Engages in preparatory meetings and feedback sessions with the team</li> <li>• Defines clear roles and responsibilities for team members for both normal and abnormal situations</li> <li>• Able to clarify team member role if required</li> <li>• Oversees team activities and decision-making processes</li> <li>• Supports other to have a level of independence in how they do their work</li> <li>• Able to synchronize and combine individual team member contributions.</li> <li>• Encourages input and information from all team members</li> <li>• Demonstrates an awareness of other team members' abilities and incorporates this into the task guidance</li> <li>• Facilitates team problem solving</li> <li>• Provide performance expectations and acceptable interaction patterns</li> </ul>	<ul style="list-style-type: none"> <li>• Does not give preparatory before an operation and/or does not give a feedback session post-operation</li> <li>• Does not clearly define the roles and responsibility for each team before an operation</li> <li>• Unable to clearly clarify roles of other team members</li> <li>• Provides minimal or no justification for actions/decisions chosen</li> <li>• Fails to combine/fully combine the contributions from all team members</li> <li>• Micromanages direct reports</li> <li>• Struggles, or shows unwillingness, to oversee team tasks/mission and is easily dictated to</li> <li>• Responds dismissively to suggestions and input from others</li> <li>• Overloads/overburdens other team members with tasks</li> <li>• Fails to facilitate team problem solving</li> </ul>

**F.3.5 Human-Machine**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Oversees team activities and decision-making processes</li> <li>Demonstrates an awareness of other team members' abilities and incorporates this into the task guidance</li> </ul>	<ul style="list-style-type: none"> <li>Provides minimal or no justification for actions/decisions chosen</li> <li>Responds dismissively to suggestions and input from others</li> </ul>

**F.4 Performance Monitoring****F.4.1 Monitoring the performance of other human team members**

The ability to develop common understandings of the team environment and apply appropriate task strategies to accurately monitor teammate performance (Salas et al., 2005).

**F.4.2 Human-Human**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Keeps an eye on other team members' tasks in order to spot possible errors or signs of overloading</li> <li>Engages with other team members to gain awareness of their physical and emotional states/preparedness</li> <li>Providing feedback regarding team member actions to facilitate self-correction.</li> </ul>	<ul style="list-style-type: none"> <li>Focuses solely on own actions and is unaware of other team members' missed cues and errors</li> <li>Ignores indications of reduced performance/adverse state in other team members (e.g. lack of communication/yawning)</li> <li>Notices other team member's errors but does not provide constructive feedback to help them correct their action</li> </ul>

**F.4.3 Human-Machine**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Monitors the MASS systems for signs of any errors</li> </ul>	<ul style="list-style-type: none"> <li>Focuses solely on own actions and is unaware of any system errors</li> </ul>

**F.4.4 Machine-Human**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Identifies potential mistakes made by the operator</li> <li>Providing feedback regarding team member actions to facilitate self-correction</li> <li>Monitors the operator's attention and/or performance</li> </ul>	<ul style="list-style-type: none"> <li>Fails to identify the operator's errors</li> <li>Notices other team member's errors but does not provide constructive feedback to help them correct their action</li> <li>Lack the ability to monitor the operator's performance or attention</li> </ul>

## F.5 Back up Behaviours

### F.5.1 Recognising and assisting when a teammate is overloaded

Ability to anticipate other team members' needs through accurate knowledge about their responsibilities. This includes the ability to shift workload among members to achieve balance during high periods of workload or pressure (Salas et al., 2005).

### F.5.2 Human-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Steps in to correct actions/understanding where required</li> <li>• Recognition by potential backup providers that there is a workload distribution problem in their team.</li> <li>• Shifting of work responsibilities to underutilized team members.</li> <li>• Completion of the whole task or parts of tasks by other team members.</li> </ul>	<ul style="list-style-type: none"> <li>• Assumes everyone has shared understanding of task without checking or fails to correct actions/misunderstanding when inconsistency is identified</li> <li>• Does not identify workload distribution problems</li> <li>• Fails to shift tasks and responsibilities to other team members with capacity</li> </ul>

### F.5.3 Human-Machine

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Steps in to correct actions/understanding where required</li> <li>• Recognises when the automated systems are out of their operating limits.</li> <li>• Takes the appropriate actions when the MASS' systems are out of their operational limits (e.g., the environmental conditions are out of limits, or the traffic density is too high)</li> </ul>	<ul style="list-style-type: none"> <li>• Assumes everyone has shared understanding of task without checking or fails to correct actions/misunderstanding when inconsistency is identified</li> <li>• Fails to recognise when the automation is out of its operational limits</li> <li>• Fails to take or does not take appropriate actions when the MASS' systems are out of their operational limits</li> </ul>

### F.5.4 Machine-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Recognises that the operator is overloaded and recommends that the system takes back certain tasks</li> <li>• Identifies situations where assistance for the operator is needed and requests assistance</li> </ul>	<ul style="list-style-type: none"> <li>• Does not identify that the operator is overloaded and fails to recommend taking back any tasks</li> <li>• Fails to request assistance from the operator in situations where it is needed</li> </ul>

## F.6 Adaptability

### F.6.1 Ability to adjust behaviour

Ability to adjust strategies based on information gathered from the environment through the use of backup behaviour and reallocation of intrateam resources. Altering a course of action or team repertoire in response to changing conditions (internal or external) (Salas et al., 2005).

### F.6.2 Human-Human/Human-Machine:

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Identify cues that a change has occurred, assign meaning to that change, and develop a new plan to deal with the changes.</li> <li>• Shows readiness for alternative actions if new information comes in during operations</li> <li>• Identify opportunities for improvement and innovation for habitual or routine practices.</li> <li>• Remain vigilant to changes in the internal and external environment of the team.</li> <li>• Is open to and ready for potential obstacles and negative outcomes during an operation</li> <li>• Is able to continue to follow procedure and maintain focus whilst under high levels of stress, distress, fatigue, or within adverse conditions</li> <li>• Shows ability to quickly adapt, switch tasks/priorities, and remain flexible to unforeseen circumstances and new information</li> <li>• Recovers quickly from setbacks and responds with renewed and increased effort</li> </ul>	<ul style="list-style-type: none"> <li>• Misses or ignores cues that change has occurred and therefore fails to develop a new plan</li> <li>• Shows reluctance to engage in contingency planning</li> <li>• Fails to recognise changes to the internal and external environment of the team</li> <li>• Shows signs of anxiety and seeks a large amount of information from other team members to satisfy uncertainty</li> <li>• Begins to perform outside of the standard procedures as a result of stress/distress/fatigue (e.g. makes basic errors during task)</li> <li>• Shuts off from task or reacts negatively (e.g. goes quiet, lowers communications, panics)</li> <li>• Continues with established task focus despite new information, failing to adapt to new circumstances</li> <li>• Constantly thinks about past disappointments or failures</li> </ul>

### F.6.3 Machine-Human:

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Identify cues that a change has occurred, assign meaning to that change, and develop a new plan to deal with the changes.</li> <li>• Is able to perform alternative actions if new information comes in during operations</li> <li>• Is ready for potential obstacles and negative outcomes during an operation</li> </ul>	<ul style="list-style-type: none"> <li>• Misses or ignores cues that change has occurred and therefore fails to develop a new plan</li> <li>• Unable to adapt plan with new information</li> <li>• Does not have the ability to adapt if there are potential obstacles or negative outcomes</li> </ul>

## F.7 Situational Awareness

The active construction of a model of a situation distributed between two or more human and/or machine team members, where each team member has their own perception, comprehension and projection of the situation (Stanton et al., 2006).

### F.7.1 Gathering information

Establishing awareness of cues from the environment internally and externally.

### F.7.2 Human-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Frequently scans the external environment</li> <li>• Demonstrates an awareness of when something in environment changes (e.g., seeks to communicate change)</li> <li>• Uses information from others (e.g. other crew members, tasking agencies) to gain overall picture</li> <li>• Refers to / checks multiple information sources relevant to mission objective</li> <li>• Maintains awareness of surroundings despite task distractions (e.g., bad weather, radio calls)</li> </ul>	<ul style="list-style-type: none"> <li>• Rarely scans the external environment information.</li> <li>• Does not request information in a timely manner, or at all</li> <li>• Carries on without realising something has happened (e.g., missing calls, missing cues)</li> <li>• Becomes fixated on task distractions.</li> </ul>

### F.7.3 Human-Machine

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Monitors systems regularly to get relevant information for their tasks and ensure awareness of warning indicators (the frequency of the monitoring will depend on the MASS system and operation)</li> <li>• Monitors, cross-checks and reports changes in the MASS system states.</li> <li>• Maintains awareness of the present state of the vessel systems and environment (position, weather, vessel traffic, terrain).</li> <li>• Demonstrates an awareness of when something in environment changes (e.g., seeks to communicate change)</li> <li>• Maintains awareness of surroundings despite task distractions (e.g., bad weather, radio calls)</li> </ul>	<ul style="list-style-type: none"> <li>• Sporadically scans user interfaces or underutilises systems when gaining awareness (the frequency of the monitoring will depend on the MASS system and operation)</li> <li>• Rarely scans physical environment information.</li> <li>• Fails to report changes in the MASS system state.</li> <li>• Does not maintain an adequate awareness of the present state of the vessel systems and environment.</li> <li>• Carries on without realising something has happened (e.g., missing calls, missing cues)</li> <li>• Becomes fixated on task distractions.</li> </ul>

### F.7.4 Machine-Human

Positive behavioural markers	Negative behavioural markers

## Appendix F

<ul style="list-style-type: none"> <li>• Demonstrates an awareness of when something in environment changes (e.g., seeks to communicate change)</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to communicate a change in the environment to their teammates</li> </ul>
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### F.7.5 Comprehending informational elements

Recognising the significance and meaning behind the information perceived to form a mental model.

### F.7.6 Human-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Recognises erroneous information from other team members or external sources</li> <li>• Exhibits a clear account of current situation and relevant task information</li> <li>• Shows awareness of risks inherent in each action taken</li> <li>• Re-briefs, suspends, or cancels action based on new risk or hazard</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to recognise, or ignores, cues that information gathered is incorrect</li> <li>• Shows a lack of understanding of current situation and associated task information</li> <li>• Demonstrates an incomplete or inappropriate awareness of risk</li> <li>• Continues action when circumstances indicate high level of hazard to crew</li> </ul>

### F.7.7 Human-Machine

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Recognises what information gained from environment and/or system means.</li> <li>• Acknowledges and seeks to share what has been comprehended/changed in the situation, prior to action.</li> <li>• Reacts appropriately to potential risks associated with comprehension of the situation.</li> </ul>	<ul style="list-style-type: none"> <li>• Demonstrates a misunderstanding of what information gained from their environment or systems means.</li> <li>• Acts based on a comprehended information but fails to share comprehension with other team members.</li> <li>• Continues with typical actions despite demonstrating an acknowledgement of risk.</li> </ul>

### F.7.8 Machine-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Recognises erroneous information from other team members or external sources</li> <li>• Exhibits a clear account of current situation and relevant task information</li> <li>• Shows awareness of risks inherent in each action taken</li> <li>• Suspends, or cancels action based on new risk or hazard</li> </ul>	<ul style="list-style-type: none"> <li>• Fails to recognise, or ignores, cues that information gathered is incorrect</li> <li>• Shows a lack of understanding of current situation and associated task information</li> <li>• Demonstrates an incomplete or inappropriate awareness of risk</li> <li>• Continues action when circumstances indicate high level of hazard to crew</li> </ul>

**F.7.9 Anticipating future states**

Projecting understanding of the situation to predict future events.

**F.7.10 Human-Human**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Plans for contingencies based upon comprehension of situation.</li> <li>Reacts in a manner suggesting preparedness for other team members actions and changes in the situation (e.g., remains calm)</li> <li>Discusses the contingency strategies with others.</li> <li>Uses available sources to manage threats.</li> <li>Prioritises primary tasks before taking secondary actions.</li> <li>Takes timely and mindful actions</li> </ul>	<ul style="list-style-type: none"> <li>Proceeds with action without engaging in contingency planning and is surprised by events that occur.</li> <li>Demonstrates a surprised response (e.g., distressed communication / sudden reflex) team members actions and changes in the situation.</li> <li>Fails to recognise a change in priority by continuing with secondary actions.</li> </ul>

**F.7.11 Human-Machine**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Plans for contingencies based upon comprehension of situation.</li> <li>Reacts in a manner suggesting preparedness for other team members actions and changes in the situation (e.g., remains calm)</li> <li>Discusses the contingency strategies with others, including taking into account the suggestions from the system, if applicable</li> <li>Uses available sources to manage threats.</li> <li>Prioritises primary tasks before taking secondary actions.</li> <li>Takes timely and mindful actions</li> </ul>	<ul style="list-style-type: none"> <li>Proceeds with action without engaging in contingency planning and is surprised by events that occur.</li> <li>Demonstrates a surprised response (e.g., distressed communication / sudden reflex) team members actions and changes in the situation.</li> <li>Fails to recognise a change in priority by continuing with secondary actions.</li> </ul>

**F.7.12 Machine-Human**

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Plans for contingencies based upon comprehension of situation.</li> <li>Discusses the contingency strategies with others.</li> </ul>	<ul style="list-style-type: none"> <li>Is unable to plan for contingencies based upon the current situation</li> <li>Does not share their contingency planning with other teammates</li> </ul>

## F.8 Shared Mental Models

An organizing knowledge structure of the relationships among the task the team is engaged in and how the team members will interact (Gisick et al., 2018; Salas et al., 2005).

### F.8.1 Understanding roles and responsibilities of self, human team members and machine team members

#### F.8.2 Human-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Shows an understanding of own role and responsibility within the team (e.g., they are performing their tasks and role within the team)</li> <li>Demonstrates an understanding of the limitations of the system</li> <li>Shows an understanding of the role the automated systems that they are working with</li> <li>Understand the role of other human team members and how their work integrates with their own</li> </ul>	<ul style="list-style-type: none"> <li>Shows confusion or lack of full understanding of own roles and responsibilities (e.g., doing tasks others are responsible for or not performing a role they are supposed to)</li> <li>Lacks awareness of the systems' capabilities and how the systems' work</li> <li>Fails to appreciate the roles and responsibilities of other human team members</li> </ul>

#### F.8.3 Human-Machine

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Shows an understanding of own role and responsibility within the team (e.g., they are performing their tasks and role within the team)</li> <li>Demonstrates an understanding of the limitations of the system</li> <li>Shows an understanding of the role the automated systems that they are working with</li> <li>Understand the role of other human team members and how their work integrates with their own</li> </ul>	<ul style="list-style-type: none"> <li>Shows confusion or lack of full understanding of own roles and responsibilities (e.g., doing tasks others are responsible for or not performing a role they are supposed to)</li> <li>Lacks awareness of the systems' capabilities and how the systems' work</li> <li>Fails to appreciate the roles and responsibilities of other human team members</li> </ul>

#### F.8.4 Machine-Human

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>Understand the role of other human team members and how their work integrates with their own</li> </ul>	<ul style="list-style-type: none"> <li>Fails to understand the roles and responsibilities of their human team members and how it integrates with their work</li> </ul>

## F.9 Trust

### F.9.1 Demonstrates an appropriate level of trust

Shows an appropriate level of reliance and use of the automated systems they are working with.

### F.9.2 Human-Machine

Positive behavioural markers	Negative behavioural markers
<ul style="list-style-type: none"> <li>• Engages the automated systems in appropriate situations</li> <li>• Demonstrates an understanding of when the automation is approaching its operating limits and takes the appropriate actions when this occurs</li> <li>• Selects appropriate levels of control for the given situation</li> <li>• Evaluates recommendations from the automated systems' before accepting or rejecting them</li> <li>• Willing to accept corrections and feedback from the automated systems</li> <li>• Uses multiple sources of information to inform their decisions</li> </ul>	<ul style="list-style-type: none"> <li>• Activates the automation in unsafe scenarios</li> <li>• Ignores or misses when the automated system is out of its operating limits</li> <li>• Recognises the automated system is out of its operating limits but does not take any action or does not take appropriate action</li> <li>• Over or under relies on the automated systems they are working with</li> <li>• Accepts recommendations from the system without fully assessing whether the suggestion is the correct course of action or rejects the recommendations without the appropriate consideration</li> <li>• Ignores or rejects corrections and feedback given by the automated systems</li> <li>• Soley relies on one information source and fails to cross reference the information with other sources</li> </ul>

## Appendix G Risk Management Framework for MASS System

### G.1 MASS Accimap in sections

Table G.2- Abbreviations used in UK MASS social network diagrams.

Hierarchical Level	Node	Abbreviation
International Committees	International Standards Organisation	ISO
	International Maritime Organisation	IMO
	United Nations	UN
	International Association of Classification Societies	IACS
	International Union of Marine Insurance	IUMI
	International Group of P&I Clubs	IGPIC
	International Labour Organisation	ILO
	International Association of Marine Aids to Navigation and Lighthouse Authorities	IALA
	International Telecommunication Union	ITU
National Committees	Transport Select Committee	TSC
	Business, Energy and Industrial Strategy Committee	BEISC
	Work and Pensions Select Committee	WPSC
	Defence Select Committee	DSC
	Maritime Research and Innovation UK	MarRI-UK
	Society of Maritime Industries	SMI
	British Ports Association	BPA
	Maritime Autonomous Systems Regulatory Working Group	MASRWG
Government	Department of Transport	DfT

	Department of Business, Energy and Industrial Strategy	DfBEIS
	Department of Work and Pensions	DfWP
	Department of Culture, Media and Sport	DfCMS
	Ministry of Defence	MoD
	Health and Safety Executive	HSE
	UK Hydrographic Office	UKHO
	Marine Accident Investigation Branch	MAIB
	Defence Accident Investigation Branch	DAIB
Regulators	Maritime Coastguard Agency	MCA
	Port and Harbour Authorities	P&H Authorities
	Defence Safety Authority	DSA
	Defence Maritime Regulator	DMR
	Office of Communications	OfCom
	Office for Artificial Intelligence	OAI
Industry	Research and Development Centres	R&D Centres
	Technology Companies	Tech Companies
	Future Autonomous at Sea Technologies Cluster	FAST Cluster
	Protection and Indemnity Clubs	P&I Clubs
Resource Providers, Management	Human-Machine Interface Designers	HMI Designers
	Royal National Lifeboat Institution	RNLI
	Software Engineers	SE
	Hardware Engineers	HE
Equipment and Environment	Maritime Autonomous Surface Ship	MASS
	Human-Machine Interface	HMI
	Remote Control Centre	RCC

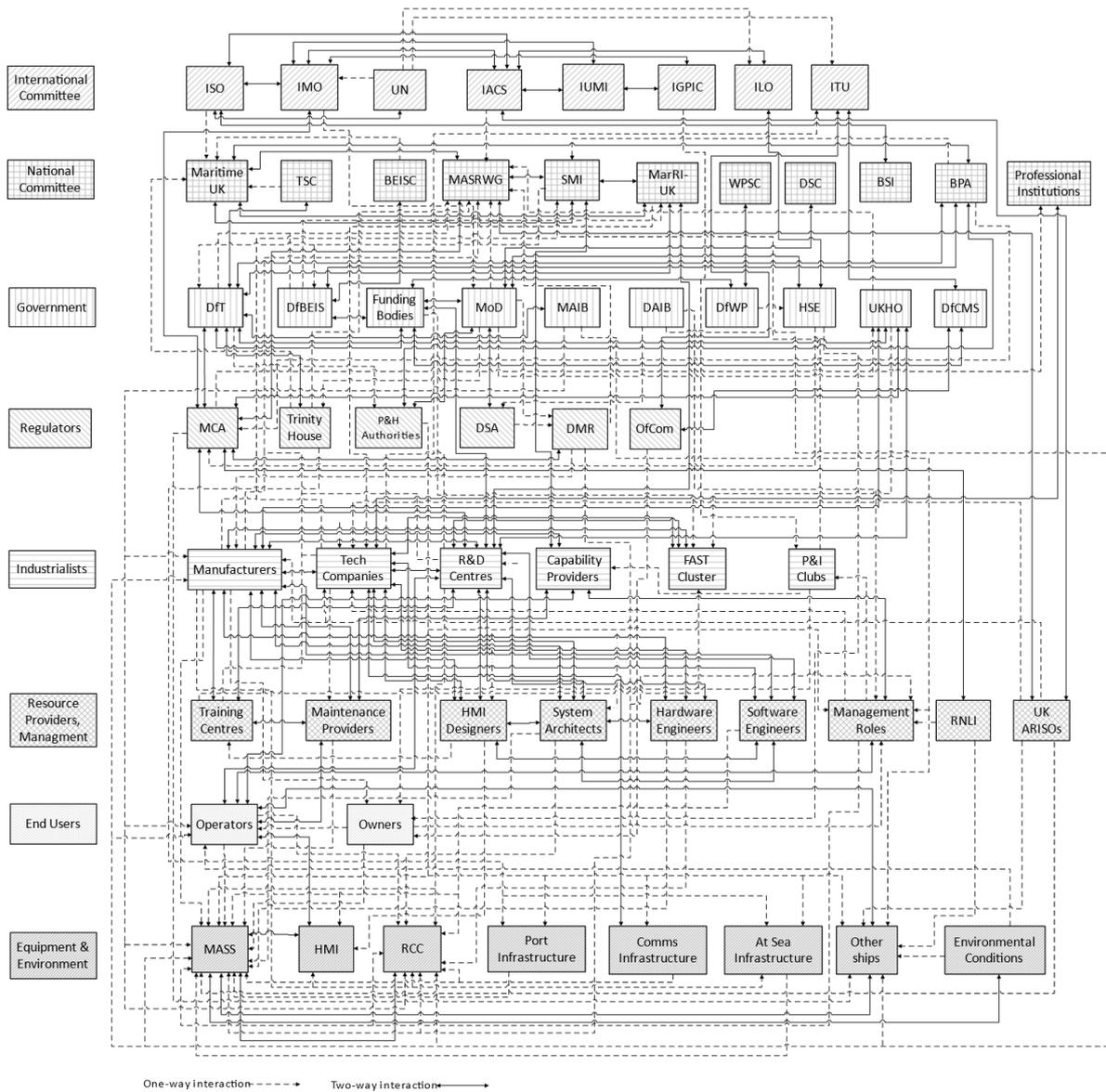


Figure G. 1- Directed social network for the current UK MASS system (note: larger dashed lines reflect one-way interaction whereas solid lines reflect two-way interaction between agents and see Table G.1 for definitions of abbreviations.)

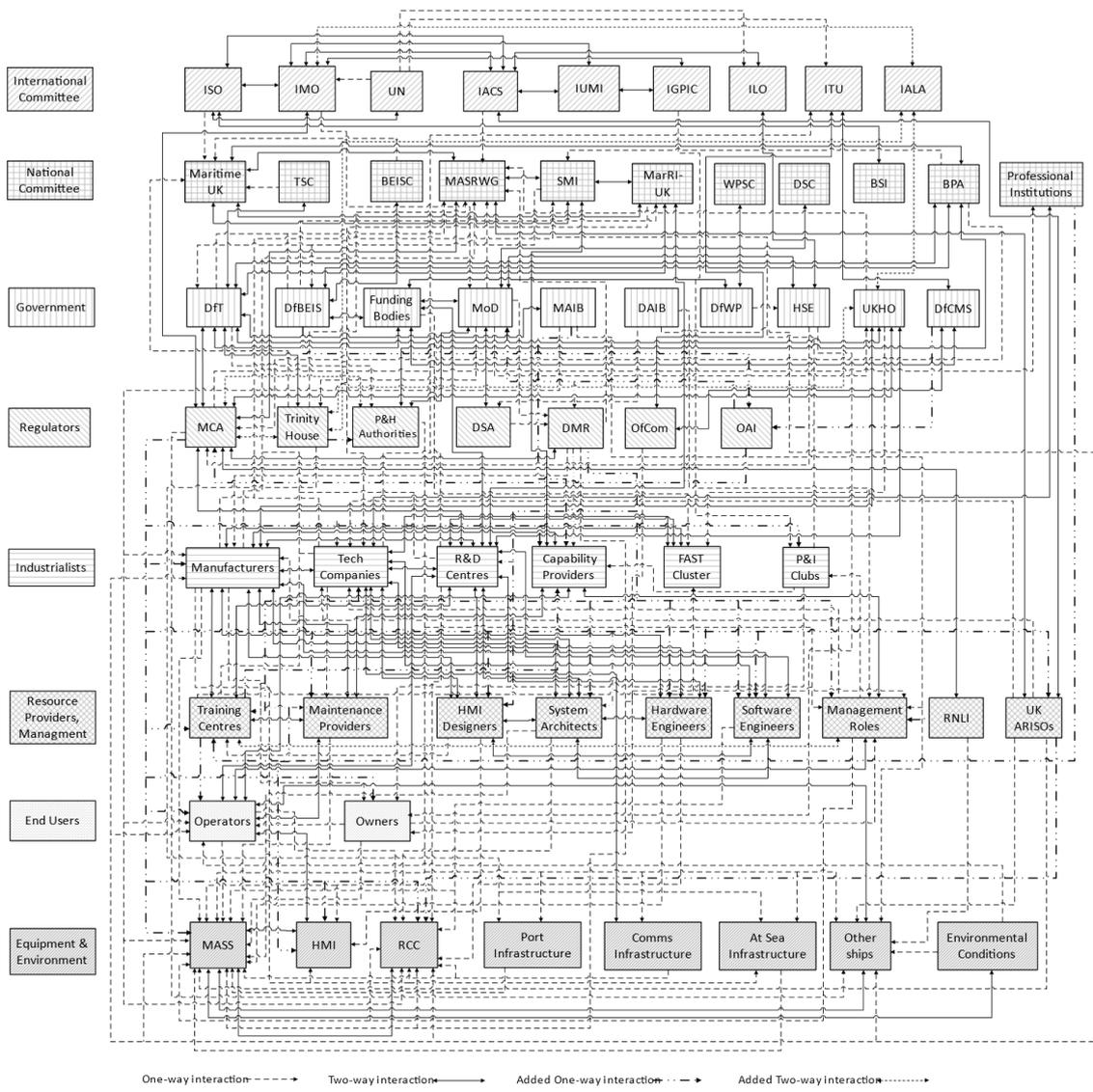


Figure G. 2 - Directed social network of the future MASS network (note: larger dashed lines reflect one-way interaction whereas solid lines reflect two-way interaction between agents. Dashed lines with dots reflect one-way interactions which have been added to create the future network and smaller dashed lines reflect two-way interactions that have been added. See Table G.1 for definitions of abbreviations).

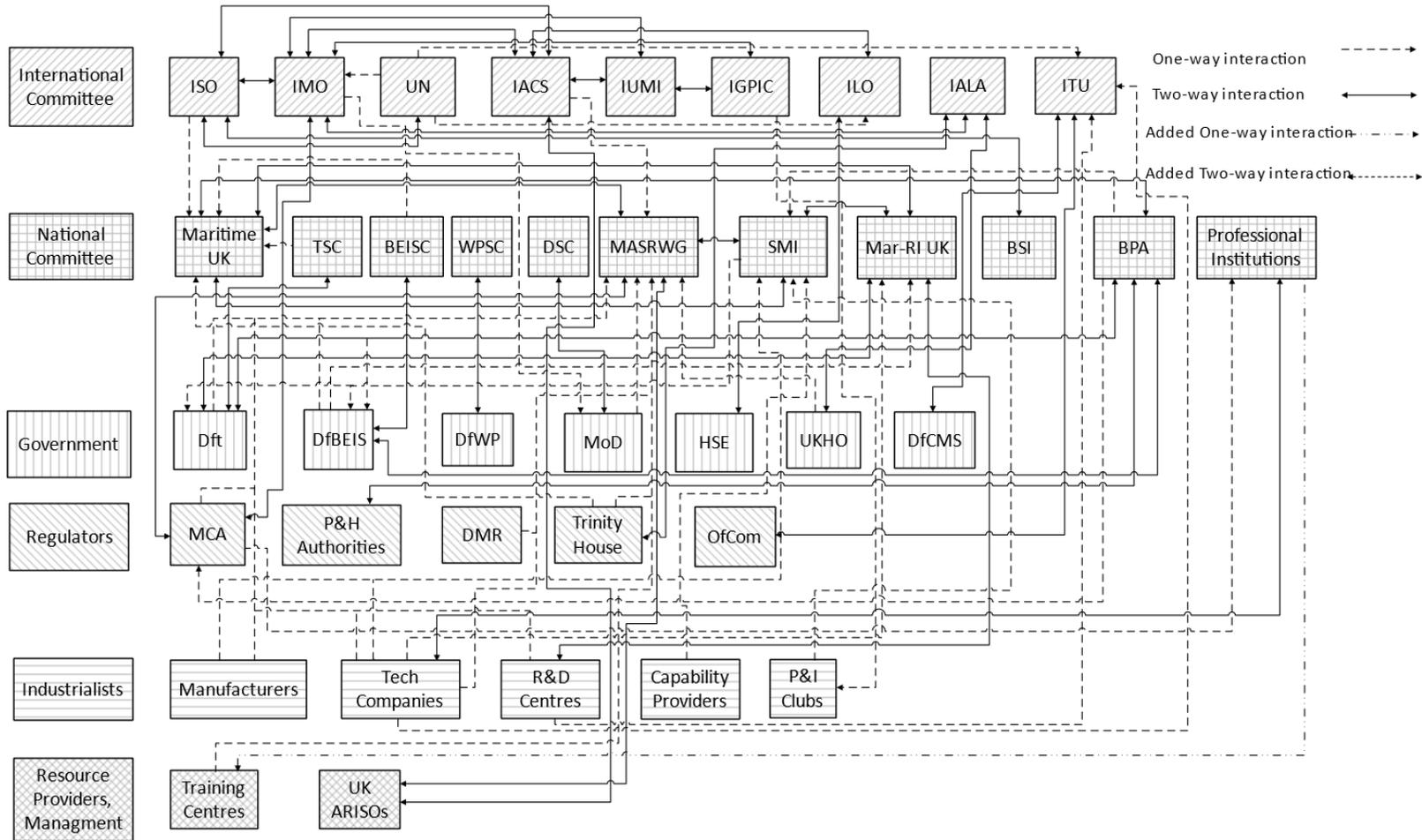


Figure G. 3 - Social network showing the international and national committees nodes' connections within the current and future MASS social networks developed.

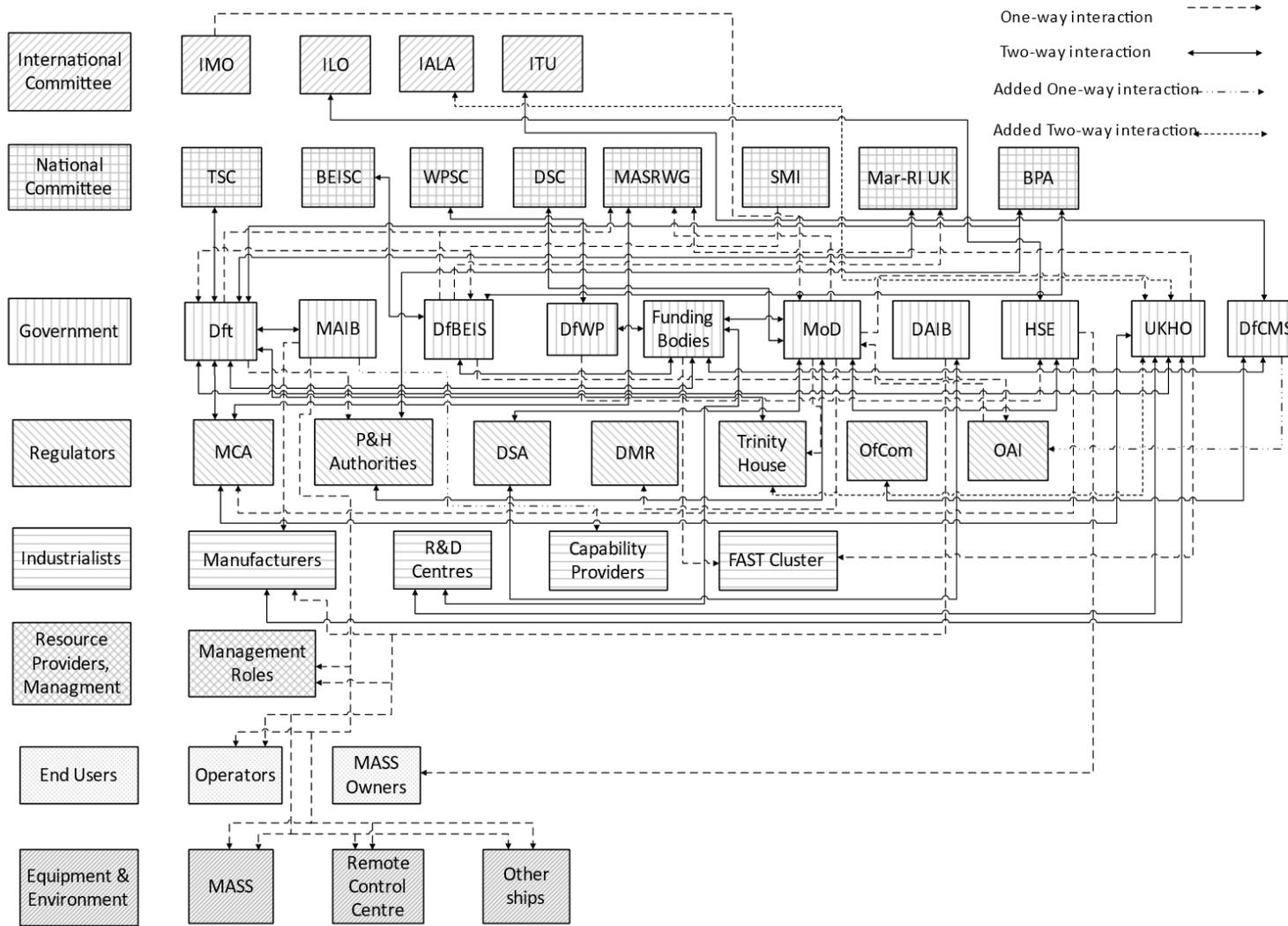


Figure G. 4 - Social network showing the government nodes' connections within the current and future MASS social networks developed.

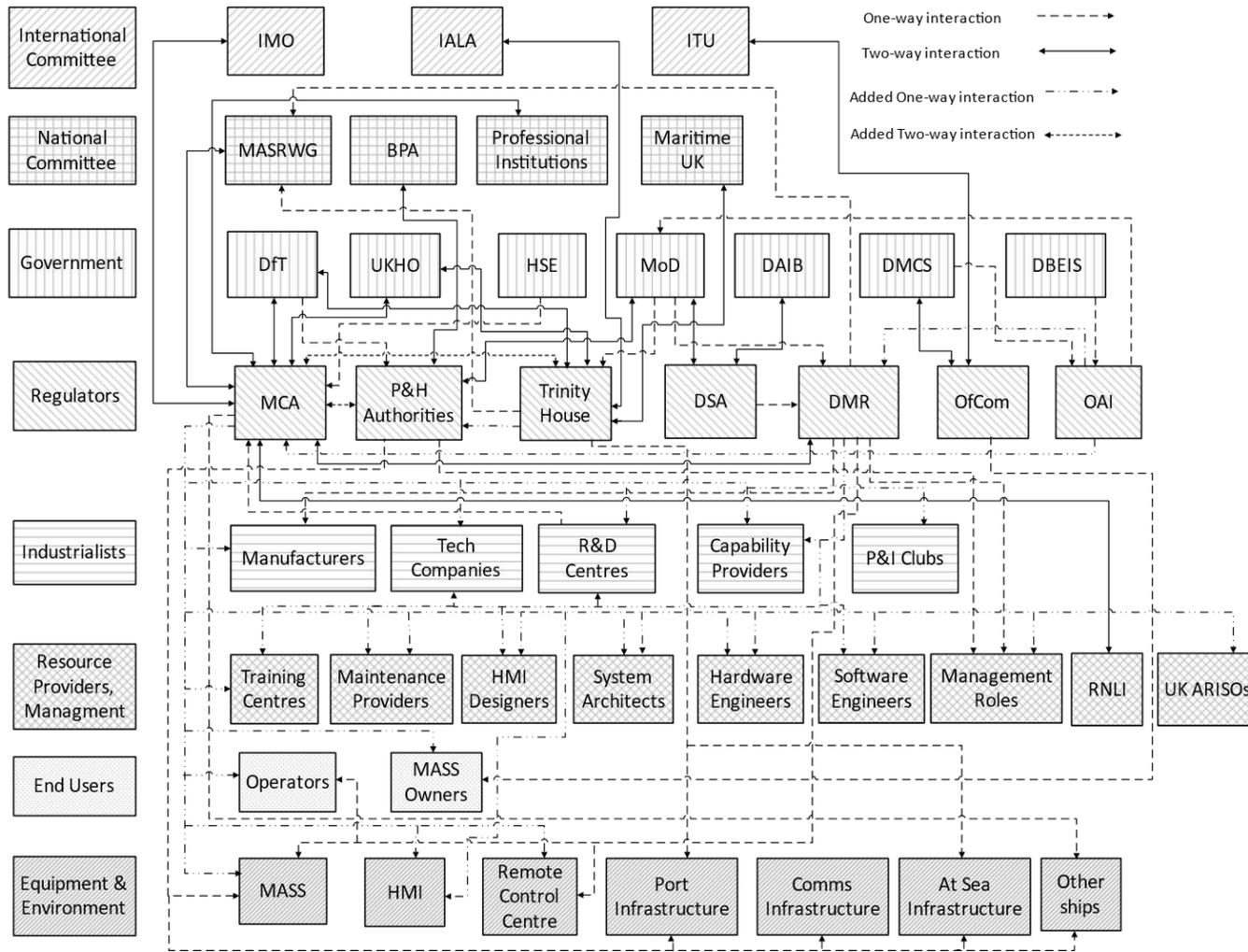


Figure G. 5 - Social network showing the regulators nodes' connections within the current and future MASS social networks developed.

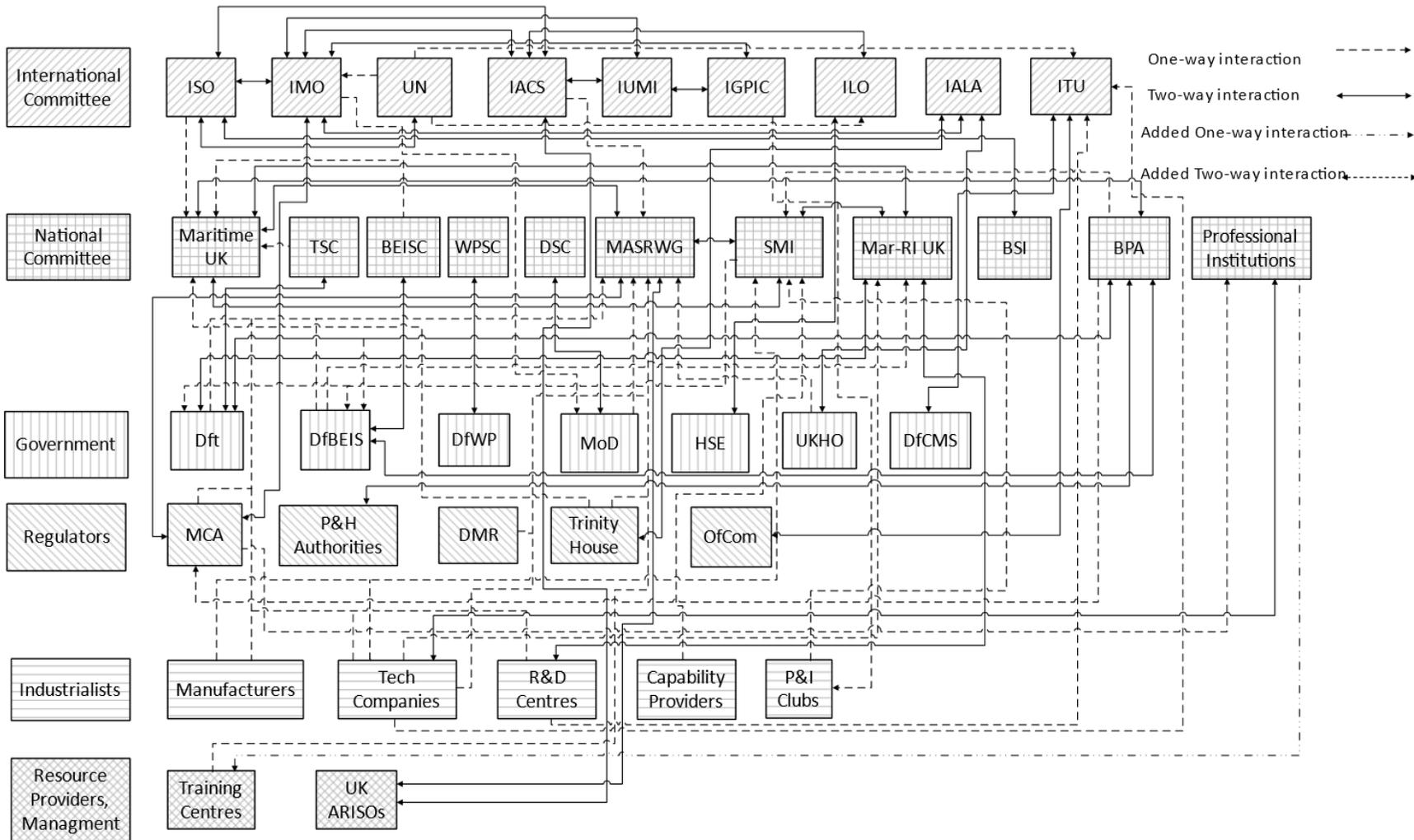


Figure G. 6 - Social network showing the industry nodes' connections within the current and future MASS social networks developed.

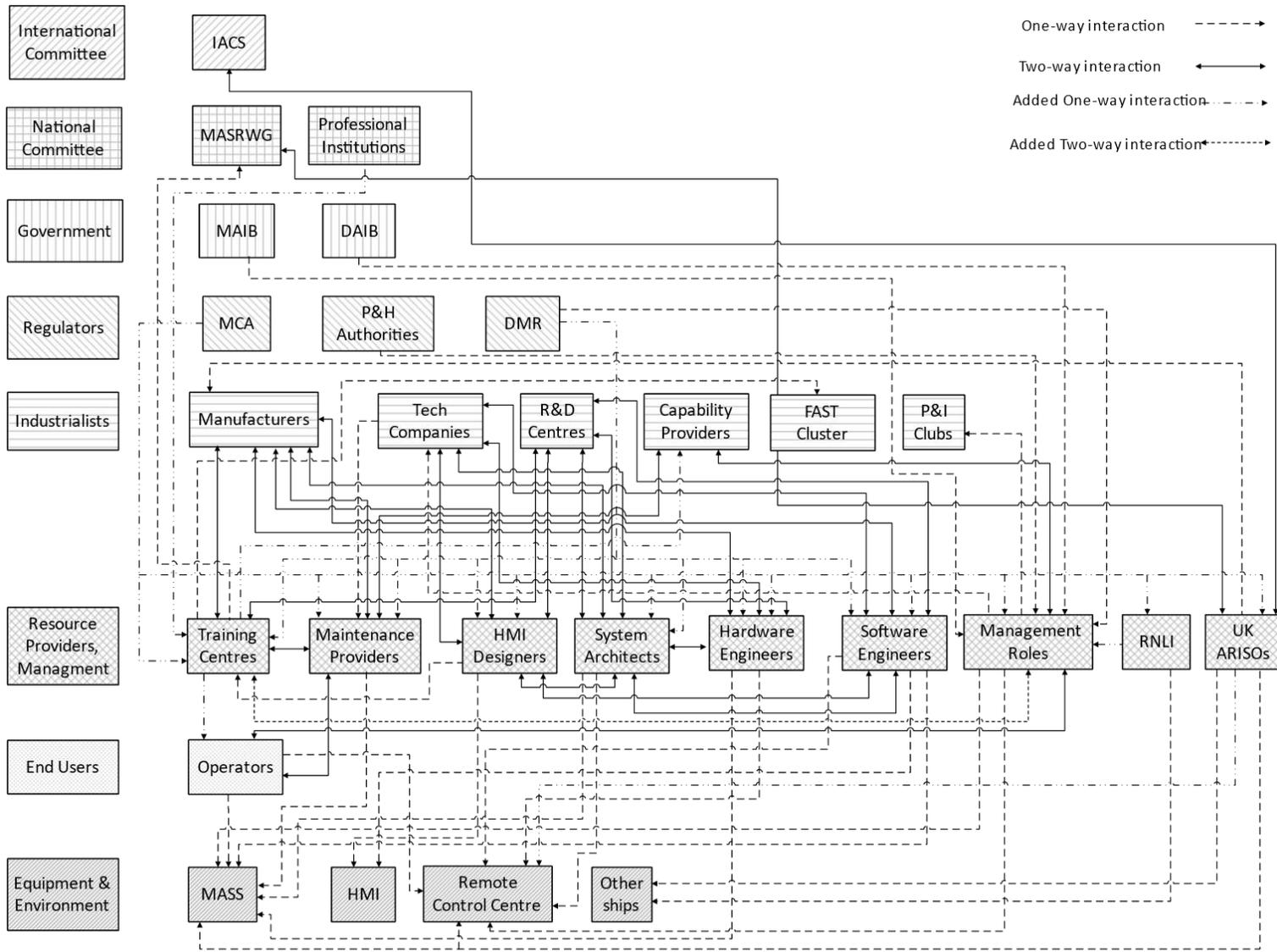


Figure G. 7 - Social network showing the resource providers nodes' connections within the current and future MASS social networks developed.

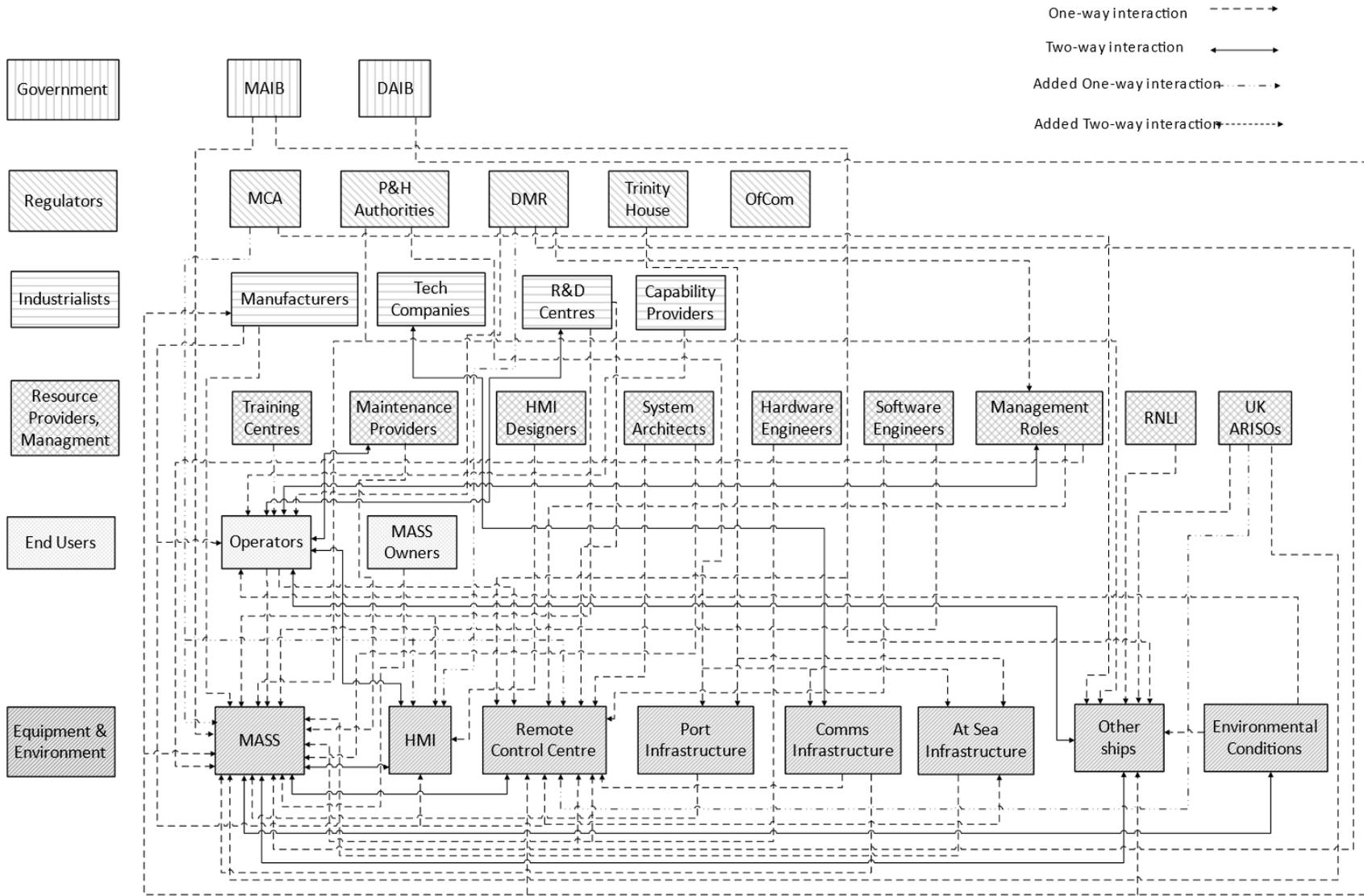


Figure G. 8 - Social network showing the end users, equipment and environment nodes' connections within the current and future MASS social networks developed.

## G.2 Social Network Analysis Results for the MASS Accimaps

Table G.3- Nodal metric results for current and future MASS networks. (Note: asterisks denote key nodes in the network)

Hierarchical Level	Node	Node Metrics													
		Emission		Reception		Sociometric Status		B-L Centrality		Closeness		Farness		Betweenness	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
International Committee	International Standards Organisation	5	5	4	4	0.15	0.15	27.32	28.22	0.33	0.35	179	174	194.87	194.46
	International Association of Classification Societies	6	6	5	5	0.19	0.18	29.97	30.21	0.36	0.36	164	168	160.42	116.71
	United Nations	4	4	1	1	0.08	0.08	23.12	24.41	0.30	0.34	197	178	14.67	12.02
	International Maritime Organisation	6	7	6	7	0.20	0.23	33.10	36.16	0.37	0.44	158	138	416.50	506.21
	International Union of Marine Insurance	3	3	3	3	0.10	0.10	26.19	26.97	0.30	0.32	195	191	4.52	3.28
	International Group of P&I Clubs	3	3	2	2	0.08	0.08	26.25	27.03	0.31	0.33	191	187	15.20	6.42
	International Labour Organisation	2	2	3	3	0.08	0.08	25.60	25.94	0.30	0.32	196	193	23.81	17.70

	International Telecommunication Union	2	2	5	5	0.12	0.11	27.65	28.43	0.24	0.26	242	237	67.75	81.04
	International Association of Marine Aids to Navigation and Lighthouse Authorities	-	3	-	3	-	0.10	-	31.10	-	0.35	-	174	-	21.11
National Committee	Maritime UK	4	4	8	8	0.20	0.20	32.63	32.32	0.32	0.33	182	187	97.34	74.8
	Transport Select Committee	2	2	1	1	0.05	0.05	27.72	28.01	0.31	0.32	192	190	0.75	0.67
	Business, Energy and Industrial Strategy Committee	2	2	1	1	0.05	0.05	25.04	24.72	0.27	0.27	221	225	0.65	0.59
	Work and Pensions Select Committee	1	1	1	1	0.03	0.03	22.79	22.60	0.25	0.25	239	243	0.00	0.00
	Defence Select Committee	1	1	1	1	0.03	0.03	26.37	26.72	0.29	0.31	201	199	0.00	0.00
	Maritime Research and Innovation UK	5	5	5	5	0.17	0.16	35.80	35.38	0.37	0.37	158	163	109.52	60.73
	Society of Maritime Industries	6	6	8	8	0.24	0.23	36.48*	35.82	0.36	0.36	165	170	234.19	211.55

	British Standards Institution	1	1	1	1	0.03	0.03	21.38	21.83	0.25	0.26	237	234	0.00	0.00
	British Ports Association	6	6	4	4	0.17	0.16	31.99	33.63	0.38	0.43	157	141	74.68	70.42
	Professional Institutions	1	2	2	2	0.05	0.07	29.51	30.13	0.29	0.3	207	206	6.66	0.54
	Maritime Autonomous Systems Regulatory Working Group	4	4	15	15	0.32*	0.31	38.19*	39.90*	0.35	0.39	168	157	251.39	228.98
Government	Department of Transport	10	10	9	9	0.32*	0.31	38.06*	39.09*	0.43	0.46	138	133	441.9	334.54
	Department of Business, Energy and Industrial Strategy	5	6	4	4	0.15	0.16	33.19	32.87	0.35	0.36	167	169	126.44	167.77
	Department of Work and Pensions	3	3	2	2	0.08	0.08	29.66	29.52	0.33	0.33	181	183	141.44	141.53
	Department of Digital, Culture, Media and Sport	3	4	3	3	0.10	0.11	29.51	30.37	0.30	0.33	194	183	99.71	125.81
	Ministry of Defence	9	9	6	7	0.25	0.26	36.02*	36.96	0.41	0.44	143	139	456.14	418.19
	Health and Safety Executive	4	4	3	3	0.12	0.11	29.58	30.85	0.36	0.41	163	150	109.18	130.16
	Funding Bodies	7	7	6	6	0.22	0.21	39.11*	38.70	0.41	0.41	144	148	605.90	499.57

	UK Hydrographic Office	6	8	5	7	0.19	0.25	37.94*	38.57*	0.40	0.42	147	146	90.66	129.67
	Marine Accident Investigation Branch	7	8	1	1	0.14	0.15	30.37	30.05	0.38	0.38	156	162	22.47	7.36
	Defence Accident Investigation Branch	7	7	1	1	0.14	0.13	24.99	24.72	0.35	0.35	169	176	10.95	5.14
Regulators	Maritime Coastguard Agency	7	28	8	12	0.25	0.66*	39.93*	46.28*	0.41	0.54	143	112	520.78	1007.83
	Port and Harbour Authorities	8	9	3	5	0.19	0.23	32.72	36.73	0.39	0.45	150	137	132.52	124.65
	Trinity House	5	9	2	5	0.12	0.23	29.74	36.16	0.33	0.43	181	141	40.25	84.27
	Defence Safety Authority	3	3	2	2	0.08	0.08	28.41	29.00	0.34	0.37	172	167	68.78	69.78
	Defence Maritime Regulator	7	17	3	4	0.17	0.34*	33.39	35.82	0.38	0.44	154	140	71.96	87.44
	Office of Communications	3	3	2	2	0.08	0.08	25.89	26.18	0.26	0.27	226	222	19.35	11.17
	Office of Artificial Intelligence	-	3	-	2	-	0.08	-	30.13	-	0.40	-	151	-	100.30
Industry	MASS Manufacturers	18	18	15	16	0.56*	0.56*	39.51*	40.31*	0.42	0.42	142	145	337.33	253.15
	Research and Development Centres	18	18	12	14	0.51*	0.52*	43.09*	45.20*	0.47	0.48	125	126	868.24	814.04

	Technology Companies	13	13	12	14	0.42*	0.44*	38.32*	39.22*	0.40	0.40	149	154	316.05	268.38
	MASS Capability Providers	5	5	6	10	0.19	0.25	34.19	35.49	0.33	0.33	180	186	111.20	81.50
	FAST Cluster	3	3	6	6	0.15	0.15	34.29	34.13	0.34	0.34	174	177	12.98	7.40
	P&I Clubs	3	3	2	3	0.08	0.10	28.48	30.69	0.30	0.30	199	206	40.28	24.96
Resource Providers, Management	Training Centres	5	8	5	8	0.17	0.26	33.29	36.27	0.35	0.37	169	166	26.63	58.77
	Maintenance Providers	5	5	5	7	0.17	0.20	31.99	33.93	0.31	0.31	191	196	21.99	14.74
	HMI Designers	7	7	5	7	0.20	0.23	32.91	35.38	0.35	0.35	170	172	2.58	2.49
	Hardware Engineer	6	6	4	6	0.17	0.20	32.91	35.27	0.35	0.35	169	172	1.10	0.80
	Software Engineer	7	7	5	7	0.20	0.23	33.10	35.49	0.35	0.36	168	171	1.90	1.56
	System Architects	8	8	6	8	0.24	0.26	33.29	35.71	0.35	0.36	167	170	2.90	2.56
	MASS Management Roles	7	7	7	9	0.24	0.26	33.00	33.73	0.32	0.32	185	193	130.00	74.69
	RNLI	1	2	1	1	0.03	0.05	23.94	31.36	0.21	0.36	279	171	2.29	0.00
	UK Authorised Recognised Surveyor and Inspector Organisation	6	7	2	3	0.14	0.16	34.09	35.06	0.38	0.39	154	156	179.54	117.57
End User	MASS Owner	3	3	4	5	0.12	0.13	29.35	30.37	0.27	0.27	216	222	85.44	43.53
	MASS Operators	8	8	11	13	0.32*	0.34*	37.20*	37.93*	0.35	0.35	168	172	544.61	476.02

Equipment and Environment	MASS	4	4	21	22	0.42*	0.43*	28.91	28.57	0.21	0.21	276	284	268.21	258.69
	Human-machine Interface	2	2	5	7	0.12	0.15	29.97	31.27	0.26	0.27	224	230	74.97	76.72
	Other Ships	2	2	8	9	0.17	0.18	30.61	31.10	0.26	0.27	224	230	135.68	78.96
	Remote Control Centre	1	1	12	14	0.22	0.25	23.99	24.31	0.18	0.18	334	344	0.00	0.00
	Environmental Conditions	3	3	1	1	0.07	0.07	28.55	28.22	0.26	0.27	223	229	73.09	75.60
	Port Infrastructure	1	1	2	2	0.05	0.05	19.79	20.41	0.18	0.18	328	339	2.03	0.75
	Communications Infrastructure	3	3	2	2	0.08	0.08	29.35	29.14	0.30	0.30	198	205	6.58	1.94
	At Sea Infrastructure	1	1	3	3	0.07	0.07	22.26	22.04	0.18	0.18	330	340	2.03	0.75
	<b>Mean Score</b>	<b>4.97</b>	<b>5.68</b>	<b>4.97</b>	<b>5.68</b>	<b>0.17</b>	<b>0.19</b>	<b>30.87</b>	<b>31.97</b>	<b>0.32</b>	<b>0.34</b>	<b>190.32</b>	<b>186.61</b>	<b>131.32</b>	<b>125.61</b>
	<b>Standard Deviation</b>	<b>3.51</b>	<b>4.78</b>	<b>4.05</b>	<b>4.48</b>	<b>0.11</b>	<b>0.13</b>	<b>5.09</b>	<b>5.50</b>	<b>0.06</b>	<b>0.07</b>	<b>45.48</b>	<b>47.65</b>	<b>179.28</b>	<b>192.02</b>

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