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Adapting High Reliability Management Framework for Enhancing Resilience in Autonomous Ships

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The increased integration of autonomous systems in maritime operations has advanced ship technology, but it also introduces new challenges for ensuring their safety and reliability. To address these challenges, this study explores the application of the High Reliability Management (HRM) framework. Rather than attempting to eliminate risks, HRM emphasizes maintaining reliable operations by continuously expanding and updating risk models to stay adaptive, even in the face of volatility, uncertainty, complexity, and ambiguity. An important aspect of HRM is its emphasis on the essential role of human operators in maintaining system safety through their ability to detect, interpret, and respond to emerging issues. Within HRM, resilience characteristics are essential as they reflect a system's capacity to adapt, recover, and maintain functionality under unexpected disruptions, often relying on the operators' expertise and decision-making capabilities to implement these characteristics effectively.
This study aims to identify key resilience characteristics (RCs) specifically for the Remote Operation Centres (ROCs) of autonomous ships, addressing their specific challenges such as maintaining situation awareness, ensuring reliable communication, and enabling effective decision-making under dynamic conditions. By embedding these RCs within the HRM framework, this study leverages HRM's principles—such as anticipation, robustness, and recovery—to systematically strengthen ROCs' operational capacities. This alignment aims to provide a basis for improved response to unpredictable disruptions, enhanced coordination in multi-vessel operations, and reduced risk of system failures during critical operations. Ultimately, these advancements contribute to the safe and reliable design of autonomous ship systems, positioning ROCs as resilient hubs capable of managing complex and high-risk maritime environments.

Keywords: High reliability management (HRM), Resilience characteristics, Autonomous ships, Remote operation centres.

1. Introduction

The development of autonomous ships has advanced through active research (MUNIN Project (2012-2015)), and autonomous ships are now being explored for commercial applications (Yara ; Kongsberg ; Zeabus). The integration of autonomous systems offers the potential for enhanced efficiency and may reduce operational costs (Nordahl, Nesheim, and Lindstad 2022; Ziajka-Poznańska and Montewka 2021). However, these technological advancements also introduce new challenges in ensuring safety and reliability (Utne et al. 2020; Alamoush, Ölçer, and Ballini 2024) , particularly in high-risk environments where human operators must manage complex systems remotely (Kuntasa and Lirn 2024; Saha 2023). Remote Operation Centres (ROCs), which serve as the central hubs for monitoring and controlling autonomous ships, might face specific demands. (Ottesen 2014; Rutledal 2024).

In addressing challenges faced by ROCs, the High Reliability Management (HRM) framework provides a promising approach. HRM emphasizes maintaining operational reliability through flexible performance strategies and proactive risk management. HRM framework highlights the critical role of human operators (Roe and Schulman 2023; P.R. Schulman 2023). The framework's principles—such as anticipation, robustness, and recovery—align closely with the concept of resilience.

While these concepts are well-studied in traditional industries, their application to ROCs in autonomous ship operations remains underexplored. This gap is particularly significant as ROCs operate in a context where human expertise must complement the capabilities of autonomous systems to ensure overall system safety.

This study therefore aims to bridge this gap by identifying resilience characteristics specific to ROCs and integrating them into the HRM framework. Through a literature review, key RCs are derived and aligned with HRM's four performance modes. This alignment provides a structured approach to managing risks in dynamic and complex maritime environments, offering practical insights for enhancing ROCs' operational resilience. The system scope is defined as the autonomous ship system directly related to ROC operators, including the ship itself and supporting operational tools (e.g., decision-support systems, communication interfaces, and remote monitoring technologies) under the ROC's control, assuming an uncrewed cargo ship operation scenario.

The remainder of this paper is organized as follows: Section 2 reviews the theoretical foundations of HRM and resilience in complex systems. Section 3 outlines the challenges faced by ROCs in autonomous ship operations and presents the proposed framework for integrating RCs with HRM, followed by a discussion in Section 4 on the implications. Finally, Section 5 concludes the study and outlines directions for future research.

2. Theoretical Background

2.1. *High reliability management (HRM)*

The HRM framework emphasizes the essential role of reliability professionals, whose specialized cognitive abilities and flexible performance strategies ensure consistent operations, even under highly variable and unpredictable conditions.

Table 1 Four performance modes and associated risks in HRM (Roe and Schulman 2008)

		System Volatility	
		High (Dynamic)	Low (Stable)
Options variety	High (Many options)	Just-in-Time	Just-in-Case
		Main risk: Misjudgment due to too many variables	Main risk: Complacency and inattention due to low operational stress
	Low (Few options)	Just-for-Now	Just-this-Way
		Main risk: Limited maneuverability, cascading errors	Main risk: Failure to meet command and control requirements

The study of organizational reliability in managing complex sociotechnical systems has been framed by the competition between two distinct paradigms. The "Normal accidents" theory posits that accidents are inevitable due to the inherent complexity and tightness of technical systems, whereas the "High Reliability Organization (HRO)" theory argues that accidents can be prevented through effective organizational management and operational practices. The HRM advances them by addressing a broader range of system states, including normal operations, disruption, recovery, and the establishment of a new normal with tailored strategies for managing reliability and risk at each stage (P. Schulman and Roe 2016). In this context, the HRM framework proposes four performance modes in normal operation, as provided in Table 1, and defines the associated risks. It emphasizes that operators must be able to navigate these performance modes flexibly, effectively managing the specific risks of each mode to ensure operational reliability.

2.2. *Resilience in complex systems*

Resilience is an essential concept for safety, particularly in the context of complex systems (Salomon et al. 2020). In the context of resilience, HRO and Resilience Engineering (RE) share common goals of understanding and enhancing safety in complex systems (Haavik et al. 2019). RE emphasizes four cornerstones for achieving system resilience: the ability to respond, monitor, learn, and anticipate, which together ensure that systems can adapt and sustain their operations under varying conditions (Hollnagel 2014). Furthermore, HRM emphasizes integrating resilience as a fundamental aspect of maintaining safe and reliable operations in high-risk environments (Roe and Schulman 2008).

By identifying and implementing resilience characteristics (RCs) tailored to the operational challenges of autonomous ships, safety may be enhanced by enabling these autonomous systems to better anticipate, absorb, and recover from disruptions. These RCs can address specific challenges such as maintaining situation awareness, ensuring reliable communication, and supporting rapid decision-making during emergencies.

3. Framework for Enhancing Resilience in Remote Operation Centres (ROCs)

3.1. *Characteristics of remote operation centres (ROCs)*

ROCs are essential for monitoring and controlling autonomous ships, providing centralized supervision and human expertise to complement automated and autonomous systems. By supporting tasks such as navigation and diagnostics, ROCs address the challenges of reduced onboard crew and ensure continuity in operations. However, ROCs face challenges such as maintaining situation awareness remotely, ensuring cybersecurity in highly digital environments, and managing the cognitive workload of operators supervising multiple vessels.

3.2. *Identifying generic resilience categories specific to ROCs*

Given that resilience is often described using high-level concepts, this paper first defines these high-level concepts as ‘generic resilience categories’ to be used in this study. Then in section 3.3, it identifies more specific RCs to address practical needs. Figure 1 presents generic resilience categories (each containing RC) that were derived from three key sources: resilience-related concepts from HRM, principles from RE, and findings from a systematic literature review. These sources are summarized below:

- HRM associates resilience with key concepts such as "anticipation," "recovery," and "robustness," which are critical for reliable operations (Roe and Schulman 2008)
- RE emphasizes foundational resilience principles, including "learning", "responding", "monitoring" and "anticipating"
- A systematic literature review by (Mottahedi et al. 2021) analyzed 192 research papers on resilience in critical infrastructure, identifying 20 resilience-related terms. Among these, "adaptability/flexibility" which is not explicitly mentioned in HRM or RE, was included as an additional key concept

Based on this, Figure 1 illustrates the relationships among identified generic resilience categories essential for a resilient system.

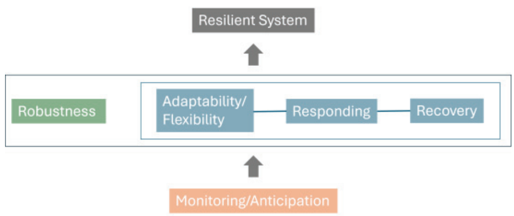

Figure 1 Identified generic resilience categories Supporting System Resilience

Robustness serves as the foundation, enabling the system to withstand disturbances. When unexpected events occur, adaptability and flexibility allow dynamic responses to changing conditions, while responding ensures timely and effective actions to address disruptions as they arise. Recovery further complements these processes by enabling the rapid restoration of functionality after system failures. These core characteristics are supported by monitoring and anticipation, which provide real-time situation awareness and enable proactive risk management. Monitoring detects potential issues, while anticipation prepares the system for emerging risks.

3.3. *Identifying resilience characteristics specific to ROCs*

To refine the general categories and derive more specific RCs applicable to ROCs, a literature review was conducted. The search was executed on the Scopus database in November 2024, and the following search string was used: TITLE-ABS-KEY ((remote operation OR remote control) AND autonomous ship AND human factors). This query resulted in 33 articles. From these, conference papers were excluded, and only journal articles were analysed. A total of 15 articles were analysed to identify the RCs related to ROCs. The results, discussion, and conclusions sections of the reviewed papers were analysed, with particular attention given to elements such as Risk Influencing Factors (RIFs), nodes from Bayesian Belief Networks (BBNs), and key findings related to human factors and system resilience. Additionally, tables and figures that highlighted operational challenges and their mitigation strategies were considered to ensure a comprehensive derivation of RCs.

In this manner, relevant factors were extracted from the analysed papers and grouped into intermediate-level categories. These categories were then refined into resilience characteristics (RCs) presented in the second column of Table 2[a].

Table 2 General resilience categories and remote operation centres (ROCs)-specific resilience strategies

Generic Resilience Categories	Resilience characteristics for ROCs	Reference
Robustness	Effective system integration and coordination	(Zhang et al. 2020) (Man et al. 2018)
	System redundance and reliability	(Yoshida et al. 2020) (Harris et al. 2020) (Lynch et al. 2024) (C. Fan et al. 2024) (Li et al. 2024)
	Strategic risk management	(Li et al. 2024)
Adaptability and Flexibility	Adaptive training and skill development	(Man et al. 2018) (Yoshida et al. 2020) (S. Fan et al. 2023) (Lynch et al. 2023) (Veitch et al. 2024) (Zhou et al. 2024)
	Flexible automation and interface design	(Harris et al. 2020) (Lynch et al. 2024)
	Human-centric and ergonomic design	(Wróbel, Gil, and Chae 2021) (S. Fan et al. 2023) (Lynch et al. 2023) (C. Fan et al. 2024) (Veitch et al. 2024) (Zhou et al. 2024) (Kari, Gausdal, and Steinert 2022)
Responding	Dynamic workload and role management	(C. Fan et al. 2020) (Zhang et al. 2020) (Wróbel, Gil, and Chae 2021) (Yoshida et al. 2020)
	Advanced decision support systems	(Lynch et al. 2024) (Zhou et al. 2024) (Kari, Gausdal, and Steinert 2022)
	Proactive error mitigation frameworks	(C. Fan et al. 2020) (Zhang et al. 2020) (Wróbel, Gil, and Chae 2021)
Recovery	Efficient emergency management systems	(C. Fan et al. 2024) (Li et al. 2024) (Zhou et al. 2024)
	Adaptive recovery decision systems	(Zhang et al. 2020) (Wróbel, Gil, and Chae 2021) (Veitch et al. 2024)
Monitoring and Anticipation	Enhanced situation awareness	(C. Fan et al. 2020) (Man et al. 2018) (Yoshida et al. 2020) (van de Merwe et al. 2024) (Lynch et al. 2024) (Lynch et al. 2023) (C. Fan et al. 2024) (Veitch et al. 2024) (Li et al. 2024)

[a] Due to page limitations, a detailed description of the process could not be included. Readers seeking further explanations are encouraged to contact the authors. The same applies to Table 3.

		(Zhou et al. 2024)
	Enhanced operator awareness and vigilance	(Zhang et al. 2020) (Wróbel, Gil, and Chae 2021)
	Efficient information management	(C. Fan et al. 2020) (Zhang et al. 2020) (Harris et al. 2020)
	Transparent and diagnostic capabilities	(Man et al. 2018) (Yoshida et al. 2020)
	Optimized dynamic workload and mental state management	(S. Fan et al. 2023) (C. Fan et al. 2024)

The allocation was determined based on each RC's primary function and impact, emphasizing its most significant role. For instance, 'Strategic risk management' might span all five generic resilience categories but was categorized under robustness due to its foundational role in mitigating risks and maintaining system stability. This broad applicability reflects the integrative nature of resilience, where multiple characteristics contribute to multiple categories depending on their context.

3.4. *Integrating the HRM framework with identified RCs for ROCs*

The RCs from Table 2 are mapped into each mode in Table 3. Each mode represents distinct operational conditions, requiring specific RCs to manage risks effectively:

- Just-in-Time demands rapid responses to dynamic scenarios with a high variety of options. Therefore, RCs that enhance real-time decision-making, situation awareness, and dynamic resource allocation were included. These RCs aim to reduce the risk of misjudgement caused by the need to process many options in real-time.
- Just-in-Case prioritizes preparedness and robustness in stable environments with many available options. RCs emphasizing effective system coordination was mapped to this mode. This helps mitigate risks caused by overconfidence or reduced vigilance in low-stress but complex operational settings.
- Just-for-Now emphasizes adaptability and mitigation strategies under volatile conditions with limited choices. RCs that support flexible adjustments, error mitigation, and adaptive strategies were included. These RCs address risks related to limited flexibility, where rapid decisions are needed to avoid escalating disruptions.
- Just-this-Way relies on predefined and robust protocols for stable scenarios with few options. RCs promoting consistency and ergonomic design were assigned to this mode. This ensures reliable adherence to established protocols, reducing risks associated with inadequate command and control structures in predictable settings.

Table 3 Alignment of identified RCs with HRM Operational Modes

HRM Performance mode	RCs for ROCs
Just-in-Time	Enhanced situation awareness
	Proactive error mitigation frameworks
	Advanced decision support systems
	Dynamic workload and role management
	Enhanced operator awareness and vigilance
	Efficient information management
	Optimized dynamic workload and mental state management
Just-in-Case	Enhanced situation awareness
	Enhanced operator awareness and vigilance
	Efficient information management
	Flexible automation and interface design
Just-for-Now	Efficient emergency management systems
	Proactive error mitigation frameworks
	Enhanced situation awareness

	Adaptive training and skill development
	Flexible automation and interface design
	Optimized dynamic workload and mental state management
	Advanced decision support systems
Just-this-Way	Human-centric and ergonomic design
	Effective system integration and coordination
	Transparent and diagnostic capabilities

Some of RCs are mapped to multiple modes. This reflects a fundamental feature of resilience: the interconnectedness and adaptability of its components across different operational contexts. This overlap highlights resilience's flexible nature, where characteristics adapt to meet diverse operational needs.

4. Discussion

4.1 *Interconnectedness and overlap of resilience characteristics*

As addressed in Section 3.4, one key insight from this study is that RCs are not entirely independent; rather, they interact and complement each other in operational contexts. Similarly, the generic resilience categories (Table 2) also overlap in their functions. For instance, in ROCs, adaptability can support recovery in scenarios like communication failures; operators who can quickly adapt by rerouting information or deploying backup systems are better positioned to restore normal operations. This interdependency might suggest that RCs in ROCs function as a cohesive system, with their effectiveness relying on how seamlessly they interact to address the complexities of managing autonomous ships.

In addition, the overlapping RCs across HRM performance modes emphasize their important role in system safety. For example, 'enhanced situation awareness' applies to three modes (Just-in-Time, Just-in-Case, and Just-for-Now), emphasizing its foundational importance for maintaining resilience in diverse operational contexts. This broad applicability establishes RCs like this as essential pillars for ensuring reliable and adaptive system performance.

Moreover, 'learning' which is widely regarded as a foundational aspect of resilience (section 3.2), has not have been explicitly identified in this study. This could be due to its implicit integration into other RCs like adaptive training or error mitigation, or the literature's focus on immediate operational needs rather than long-term resilience-building processes. The role of learning in ROC requires further study to understand its practical contribution to resilience. Mechanisms such as near-miss analysis, incident reporting, and feedback loops could integrate lessons from operations, enhancing adaptability and long-term system performance.

4.2 *Addressing operational risks through HRM and RCs*

The allocation of RCs to specific HRM performance mode, as shown in Table 3, emphasizes a structured approach to systematically managing risks. By leveraging the HRM framework, RCs are strategically aligned to address the main vulnerabilities associated with each mode, providing a targeted and effective means of risk mitigation. This integration represents the foundation for RCs to move beyond conceptual framework and align more effectively with the operational demands of ROCs.

4.3*Challenges and future works*

Future research should address the challenges of translating RCs into implementable safety requirements and design specifications. The inherent interconnectedness of RCs complicates their categorization, and their context-dependent nature requires further empirical validation. Future research could explore methods for quantifying the interactions among RCs and evaluating their combined effects on operational resilience in ROCs. Additionally, examining how these interactions evolve in real situations, such as during disruptions or high-stress scenarios, could provide deeper insights into their practical applicability. Furthermore, gathering input from experts could help refine the RCs, ensuring it addresses the specific challenges faced in operational settings.

5. Conclusion

This study presents the integration of resilience characteristics (RCs) with the High Reliability

Management (HRM) framework to address the safety challenges of Remote Operation Centres (ROCs) in autonomous ship operations. The alignment of RCs with each HRM performance mode, as outlined in Table 3, demonstrates their relevance in addressing the key challenges faced in different operational contexts. These results could provide a theoretical foundation for integrating RCs within the HRM framework in autonomous ship operations. The RCs defined in this study can serve as a basis for future empirical validation to further refine resilience aspects in ROCs. This structured approach should contribute to deriving requirements to safer design thereby strengthening the ability of the ROCs to maintain reliability under varying conditions. The findings emphasize the interconnected nature of RCs and show how their combined application may enhance the resilience of ROCs. Moreover, the study shows the importance of applying RCs flexibly across HRM performance modes to develop practical problem solving and decision-making strategies that cover the unique demands of specific operational contexts for human operators.

Further research should focus on validating the proposed framework through practical applications, exploring the interactions among RCs, and identifying ways to further strengthen resilience in real-world scenarios.

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