Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen

doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P4905-cd

Designing HMI for remote operation of urban autonomous ferries with CRIOP

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Autonomous urban passenger ferries are emerging as an efficient solution for public transportation, allowing operators to supervise multiple vessels from a Remote Operation Centre (ROC). A recent milestone demonstrated the remote operation of MF Estelle, the world's first commercial autonomous ferry, from 600 km away. As operations shift from onboard to remote environments, designing a new Human-Machine Interface (HMI) becomes critical. This paper reflects on three key phases of work informing the development of a robust ROC HMI. (i) **Phase 1**: The milliAmpere2 trial in 2022 marked the first public demonstration of the ferry's autonomy system, revealing the need for an HMI to display system status and decisions clearly. (ii) **Phase 2**: Building on lessons learned from the trial, a user-friendly HMI was designed for MF Estelle. However, pursuing a human-centred design approach was challenging due to the undefined operator role for autonomous ferries. Despite these difficulties, the HMI was successfully integrated on board Estell. (iii) **Phase 3**: After over a year of operation, the need for a ROC became apparent. The transition from onboard to remote control presents significant challenges. To address this, a CRIOP workshop was conducted, identifying critical issues related to human factors, such as the necessity of comprehensive task analysis and the importance of situation awareness (SA) in supporting the ROC operator. The results emphasize the importance of automation transparency, reducing cognitive workload, and systematically integrating human factors. Achieving fully remote operations requires both a well-designed HMI and a supporting infrastructure. This paper consolidates years of work in identifying and addressing HMI design challenges, offering insights to support meaningful human control and ensure safe transitions from onboard to remote operations.

Keywords: Autonomous Urban Passenger Ferry, Human-Machine Interface Design, Remote Operation Centre, Human-Centred Design, Meaningful Human Control

1. Introduction

The development of autonomous systems and their remote operation has been advancing across various industries, particularly in transportation. Autonomous urban passenger ferries are emerging as a sustainable and efficient alternative to land-based transportation in urban areas, promising reduced congestion and environmental benefits (Goerlandt & Pulsifer, 2022; Namireddy et al., 2019). However, transitioning from traditional ferry operations to fully autonomous systems introduces significant technological and operational challenges.

Although the ultimate goal of autonomous ferries is fully autonomous and crewless operation, current regulatory requirements (European Parliament, 2024) mandate human involvement (i.e. Human Oversight) in Remote Operation Centres (ROC) as a fallback to ensure timely intervention in case of unexpected events and to mitigate potential consequences. This reliance on human oversight makes the design of effective Human-Machine Interfaces (HMI) a critical component of autonomous ferry systems, as HMIs serve as the primary medium for interaction between human operators and the autonomy system.

This paper reflects on the journey of developing HMI solutions for autonomous ferries, focusing on key milestones: the milliAmpere2 trial, the design of HMI for MF Estelle, and the CRIOP workshop (Crisis Intervention and Operability analysis) conducted to assess and identify challenges in ROC development. These milestones not only demonstrate the progress of autonomous ferries but also highlight the evolving understanding of HMI design to ensure meaningful human control (MHC).

1.1. *Stakeholders of autonomous passenger ferries*

The stakeholders of autonomous passenger ferries are diverse, and those who directly interact in operation with such ferries can be categorized into four groups: developers, operators (including emergency response), passengers, and other vessels (Veitch & Alsos, 2021a). Communication between the ferry and these stakeholders was traditionally the responsibility of the onboard safety hosts (or operators) based on the requirements given to the developers. However, as this role transitions to the ROC, the absence of operators necessitates complementary HMI designs and the development of multiple HMIs to address these requirements effectively. Stakeholders are:

- **Developers** monitor the autonomous system to ensure its functionality, address emerging issues, and implement updates to enhance performance and reliability (Veitch & Alsos, 2021a).
- **Operators** oversee navigational operations, manage ship systems, and ensure passenger safety, which are critical

responsibilities for maintaining safe and efficient ferry operations (Veitch et al., 2021b).

- **Passengers** interact with the system through various touchpoints, such as ticketing, boarding, information/ communication during the trip, and disembarking (Petermann et al., 2024).
- **Other vessels** navigating shared waterways with the autonomous ferries require clear communication of the autonomous ferry's operational intentions, particularly in scenarios involving close trajectories or potential collision risks. Research suggests the need for external interface designs that display an autonomous ferry's navigation signals to enhance safety (Simic & Alsos, 2023; Porathe, 2021).

This shift to more autonomous remote operation requires multiple HMIs to be created and adapted to the new operational environment, ensuring seamless interaction and effective communication between stakeholders and the system. This paper focuses specifically on the operator's HMI, exploring how its design can address the unique challenges of remote operation, enhance situation awareness (SA) (Endsley, 1988), and ensure meaningful human control.

1.2. *HMI design for autonomous passenger ferries*

Recent international studies on HMI design for autonomous systems have identified several important trends. In the automotive sector, research underscores the significance of building trust and ensuring transparency in human-AI interactions (Calvert et al., 2019). Aviation research has concentrated on minimizing cognitive workload through intuitive interface designs and reliable alarm systems (Endsley, 2019). Similarly, in the maritime industry, Porathe (2021) and Rødseth (2017) have investigated the complexities of remote monitoring and control for autonomous vessels, highlighting the necessity for clear communication of operational intentions and robust SA tools. These findings offer valuable guidance for developing HMIs that enhance meaningful human control in autonomous ferry operations.

HMI design for autonomous passenger ferries requires the creation of intuitive and effective interfaces that enable seamless communication between human operators and autonomous systems. A Safety Critical Task Analysis serves as the foundation for designing these interfaces, outlining the essential tasks required for safe and efficient operations. Additionally, Task Analysis is instrumental in evaluating cognitive workload, ensuring that the HMI supports operators' decision-making without overwhelming them. Key HMI concepts considered in this analysis include:

- **User-Centered Design**: Integrating feedback from operators and stakeholders to ensure the HMI aligns with their needs, thereby supporting meaningful human control (ISO 9241-210, 2019).
- **Support for Situational Awareness (SA)**: Enabling operators to perceive, understand, and anticipate the state of the ferry and its environment, thereby enhancing decision-making (Endsley, 1988).
- **Automation Transparency**: Ensuring that operators have a clear understanding of the autonomous system's decision-making processes and actions, including at least the ability to anticipate the upcoming behaviour of the ferry operation (van de Merwe et al., 2023).
- **Cognitive Workload Management**: Designing interfaces that optimize mental effort and enhance operational efficiency, minimizing cognitive overload for operators Ecological Interface Design (EID) supports this by providing information in a way that aligns with human cognitive abilities, enabling more intuitive decision-making and reducing unnecessary mental strain (Vicente & Rasmussen, 1992).
- **Alarm Systems**: Developing alert mechanisms that prioritize critical notifications and minimize false alarms to support timely and accurate decision-making (EEMUA 191, 2024).

These HMI concepts are essential for maintaining safety and operational efficiency in remote operations, particularly for autonomous ferries where operators depend entirely on the HMI for situational awareness and decision-making.

1.3. *Transition towards remote operation centres*

The transition from traditional onboard ferry operations to ROCs for autonomous passenger ferries requires a fundamental rethinking of human operator roles and tasks. Carefully designed HMIs are essential to support and complement these changes. As autonomous ferries become more autonomous, human operators will no longer supervise a single designated vessel from a ROC. Instead, their responsibilities will expand to managing a broader range of capabilities, ensuring safety, efficiency, and timely intervention when required (Porathe, 2022).

Previous research has hypothesized various forms of remote operations. Initially, operators will oversee navigation, system monitoring, and safety. In complex environments, such as congested ports or intricate archipelagos, operators may need to assume direct control to ensure safety (Aarset et al., 2024; Rødseth, 2017). For long-voyage autonomous vessels traveling across multiple time zones, collaborative monitoring between corresponding ROCs aligned with the vessel's time zone can help maintain oversight (Porathe, 2014).

As autonomy increases, the number of vessels under an operator's supervision will grow, reflecting a shift from direct control to supervisory roles. A critical aspect of ROC design is the seamless transition of control between autonomous systems and human operators. However, as autonomy increases, the operator's role evolves into supervision, where intervention is only required in complex or unexpected scenarios.

When autonomous systems detect anomalies and alert operators, human-out-of-the-loop issues may arise (He et al., 2022). Operators, who have not been actively engaged in the decision-making process may struggle to regain SA promptly, delaying interventions. Two major problems can occur during interventions: The first problem is the complexity of the decision process: Operators must rapidly interpret the situation and make decisions, potentially affecting the quality and relevance of their input. The second problem is interrupting autonomous processes: Halting an autonomous system mid-operation may disrupt its internal processes, leading to unintended risks or consequences.

To ensure smooth and safe operations, particularly in dynamic and unpredictable environments, the ability to seamlessly transition between autonomous and manual modes must be carefully designed. This includes robust HMI integration, clear role definitions, and support for operator situational awareness and decision-making capabilities, supporting "Situation at a glance" functionality.

2. Method

This study consolidates a series of efforts conducted over the years (2022-ongoing) to design HMI for ROC in autonomous passenger ferry operations (see Table 1).

Table 1. Timeline of key events, activities, and stakeholders of this study (HF*: Human Factors)

	2022 September (3 weeks)	2023 Jan.-May (5 months)	2024 August (2 days)
Key event	Trial operation of milliAmpere2	Design of MF Estelle's HMI	Conducting a CRIOP workshop
Activity	Collecting data, Logbook analysis	Usability test, Operator feedback	Identify key challenges of designing ROC
Stake holders	NTNU researchers, Safety host, Zeabuz developers	NTNU Designers, Zeabuz developers, Safety host	Torghatten Operators & managers, Zeabuz developers, NTNU & SINTEF HF* experts

These efforts were undertaken as distinct yet interrelated phases, each addressing specific challenges and contributing to the overall understanding and development of effective HMI solutions.

This research follows an iterative, human-centred approach to designing an HMI for the remote operation of autonomous ferries. The process is organized into three interconnected phases, progressing from real-world observations to iterative design and culminating in CRIOP, which serves a dual purpose: supporting safety validation for the onboard HMI design and current operation concept and identifying key challenges for designing the ROC.

It consists of three phases: (1) Logbook analysis and system insights from the trial operation, (2) HMI design and iterative usability testing, and (3) Safety validation and identification of key challenges through a CRIOP workshop, informing both the onboard HMI and ROC design. The following sections elaborate on the methodology applied in each phase.

Phase 1: milliAmpere2 trial operation

The first phase focused on reviewing data collected during the trial operation of milliAmpere2 (Alsos et al., 2024; Veitch et al., 2024). Operators and technicians were asked to log system errors, abnormal operations, and instances of good performance. This included analysing operator logbooks and autonomy system performance records to identify key operational challenges and user interactions.

Phase 2: HMI design for MF Estelle

Building on the insights from Phase 1, this phase focused on designing and integrating HMI systems for the MF Estelle ferry. The design process followed a Human-Centred design approach and consisted of four key stages:

(1) Co-design Workshop with participants from the trial operation and *User Interviews* with the operators of the milliAmpere2 trial operation. This approach engaged stakeholders to gather valuable insights into operator needs and challenges.

(2) Establishing User Scenarios and Requirements based on the insights from the workshop and interviews.

(3) Iterative HMI Design and *Usability Testing,* incorporating feedback from usability tests with researchers, developers, and operators to refine the interfaces.

(4) Finalization and *Implementation* in collaboration with front-end developers to ensure seamless integration with the autonomy system.

A significant limitation of this phase was the absence of the actual MF Estelle operator, as the operator had not yet been hired or identified at the time. Thus, the user-centric view was challenging to document/ implement.

Phase 3: CRIOP workshop for ROC HMI design

Phase 3 involved a 2-day CRIOP workshop (Johnsen et al., 2011) to identify challenges in the design of the ROC. The CRIOP methodology, originally developed for the oil and gas industry, was adapted to assess human factors and safety requirements specific to remote operation centres. The workshop consisted of three main components:

- **Checklist Analysis:** A detailed review of the current operation and ROC design against best practices in human factors, including HF standards such as ISO 9241-210 (2019) and IEC 63303 (2024), Alarm standards such as EEMUA 191 (2024), and Safety Critical Task analysis (Energy institute, 2020).
- **Scenario Analysis:** Exploration of critical scenarios, such as fire onboard the ferry, loss of communication with the ROC, and collision or grounding, to identify potential risks and mitigation strategies.
- **Collaborative Learning Arena:** A forum for operators, designers, and management to share insights and refine the ROC design based on practical experience.

This structured approach facilitated a comprehensive analysis of HMI and ROC design, aiming to enhance safety and reliability while addressing the challenges posed by increased digitalisation, autonomy, and remote operation.

3. Results

Phase 1: Insights from milliAmpere2 trial operation

In 2022, milliAmpere2 (Eide et al., 2025), developed by the Norwegian University of Science and Technology (NTNU), underwent a three-week trial operation in a real-world environment, open to the public (Alsos et al., 2024). A safety operator equipped with professional nautical expertise and safety training, was onboard to ensure passenger safety, manage emergencies, and oversee compliance with COLREGS (IMO, 1972).

The trial demonstrated the autonomy system's capabilities, such as effective target tracking and collision avoidance in a challenging environment with leisure boats and currents. However, operator logbooks (see Table 2) recorded approximately 25 manual interventions during the three-week trial. Some autonomy system behaviours - such as unexpected acceleration or halting due to misinterpreting floating fragments as obstacles - were not immediately comprehensible to the operator (Eide et al., 2025). These incidents underscored the need for an HMI design that enhances transparency, usability, and operator comprehension of the autonomy system's decisions, forming a foundation for the operator's decision-making.

Table 2. Logbook summary

Category	Qty.	Description
Positive log entries	-	Operational logs without issues
Boat interactions	53	Encounters with other vessels
System Problems	15	Technical issues affecting system performance
Tracking problems	40	Issues related to object detection and tracking
Strange track	*7*	*Correct detection but display error*
Lost track	*2*	*Object detection lost*
Late track	*4*	*Delayed object detection*
False track	*27*	*Misidentification of detected object*
Stops	*25*	*Stops due to False track*
Speed	*2*	*Speed changes due to False track*
Unknown error	1	Error with unidentified cause

Phase 2: HMI design and integration for MF Estelle

Building on insights from the milliAmpere2 trial, the MF Estelle was developed for commercial transport in Stockholm, with its launch in May 2023. The autonomy system for the vessel was designed and developed by Zeabuz, a spin-off from NTNU, prioritizing safety and reliability for commercial operations. The design of the HMI was one of the key aspects that aimed to support SA, facilitate autonomous crossings, and provide transparency into the decision-making processes of the autonomy system.

The results and takeaways from each design process are as follows:

(1) Co-design Workshop and User Interviews: The HMI should be clear and intuitive, avoiding information overload or excessive user involvement, such as acknowledging all detected targets. This approach aims to reduce cognitive workload.

(2) Establishing User Scenarios and Requirements: Scenarios were identified and analysed to design an effective alarm system and to understand how operators could react or intervene using the HMI.

(3) Iterative HMI Design and Usability Testing: Some dilemmas emerged as users expressed a need for the HMI to project the ferry's upcoming behaviour in various situations. However, providing too many explanatory components or visual cues increased cognitive workload. Additionally, while alarms (e.g., for approaching objects) were deemed necessary to maintain appropriate SA, a fully autonomous system would ideally manage such scenarios independently, reducing the need for explicit alerts. Usability testing was instrumental in refining the HMI design for MF Estelle. During the iterative testing phase, operators provided feedback on the interface's clarity, ease of use, and support for SA. Key findings included:

- The need for simplified visualizations to minimize cognitive load.
- The importance of consistent colour coding and symbols for quick information processing.
- The effectiveness of bird's-eye-view displays in enhancing navigational support.

These insights guided the final design, prioritizing usability and operator comprehension while aligning with industry standards such as IEC 62288 (2021) and the OpenBridge design system (OICL, 2024).

(4) Finalization and Implementation: Ultimately, the HMI was designed to enhance usability and reduce cognitive load, as illustrated in Figure 1. To achieve this, it provides (i) an overview of the autonomy system's health status, (ii) a control menu with two slide buttons - one to enable autonomy and another to initiate crossings, and (iii) a separate menu for detailed crossing adjustments, including selecting a destination dock (either from the left menu or directly on the map) and pausing crossings (station keeping).

Fig. 1. Operator interface of MF Estelle (Source: Zeabuz)

(iv) Manual handovers were facilitated through both the HMI and a manual DP console. Additionally, the operator can utilize autonomy in speed override mode, where autonomy ensures the vessel stays along the nominal path while allowing the operator to adjust the speed using a lever. The lever is located beneath the interface as shown in Figure 2.

The OpenBridge design system was applied to the ECDIS, incorporating its standardized buttons, layouts, and design principles. Specifically, (v) AIS and (vi) radar-detected objects were displayed using icons derived from interpretations of IEC 62288 (2021). This approach enhances usability and ensures the interface remains easily comprehensible for users, as OpenBridge is widely adopted within the industry (OICL, 2024).

Fig. 2. Console on the bridge of MF Estelle – lever beneath the interface (Source: Zeabuz)

To reduce cognitive load, alerts for nearby obstacles were removed, and colour coding was applied to the (vii) trajectory to visually indicate speed changes or stops as determined by the autonomy system: normal (green), slow (red), and fast (dark green). This visualization helps the operator anticipate and project potential actions more effectively.

Phase 3: Challenges identified through the CRIOP workshop

The CRIOP analysis provided valuable insights for the design and development of the HMI within the ROC. While a broader discussion of the workshop findings, including organizational and operational aspects, is presented in (Park et al., 2025), this section focuses specifically on HMI-related considerations.

The analysis emphasized that task and cognitive work analyses are foundational to effective HMI design. The HMI should be developed based on a clear understanding of operator workflows and mental demands, aligning with recognized standards such as IEC 63303 (2024) and the OpenBridge design system (OICL, 2024). This ensures that the interface supports SA (Endsley, 1988) by presenting information clearly and consistently, enabling operators to rapidly detect and project the events. Consistent use of symbols, formats, and colour coding was identified as a key strategy for improving usability and reducing cognitive load (OICL, 2024).

Automation transparency was highlighted as an essential aspect of HMI design. The interface must allow operators to understand the system's behaviour and anticipate its actions, especially in scenarios where manual control may need to be assumed. Alarm systems also play a central role in HMI usability. Recommendations included basing alarm design on hazard analyses and adhering to best practices, such as EEMUA 191 (2024), to minimize false alarms and prioritize essential notifications. Clear, concise, and actionable alarm texts were emphasized as critical for operator decision-making.

Supporting tools, such as 360-degree bird's-eye-view displays and CCTV systems designed in compliance with ISO standards (e.g., IEC 62672 (2018)), were recommended to enhance SA. These tools should provide clear visual information and ensure low latency for real-time synchronization, effectively supporting navigation and monitoring tasks. Furthermore, systematic user testing, including scenario-based evaluations, was identified as critical for refining the HMI and ensuring its usability and reliability under diverse operational conditions.

4. Discussion

4.1. *Challenges in HMI Development for MF Estelle*

Several challenges arose during the development of the HMI for MF Estelle, highlighting important considerations for future work. First, the absence of hired operators for the vessel limited the ability to gather feedback from the intended end-users, relying instead on safety hosts from the milliAmpere2 trial and experiences from a conceptual ROC lab (Veitch et al., 2021b). Second, the simultaneous development of the HMI and the autonomy system introduced uncertainties about required functionalities, equipment interactions, and the execution of task analysis. Third, managing alarm systems and reducing cognitive load emerged as significant concerns. The initial design of the operator interface, as shown in Figure 3, incorporated colour-coded icons and pop-up alerts for objects entering safety boundaries, which required operator confirmation. While this approach addressed SA issues, it inadvertently increased operator effort, created distractions, and risked cognitive overload. These challenges highlight the need to balance SA and cognitive workload, as ROC operators may become out-of-the-loop.

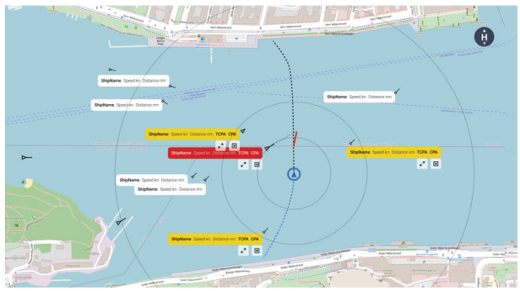

Fig. 3. Initial design of the operator interface

4.2. *Regulatory requirements and human-centric development*

The EU Artificial Intelligence Act (European Parliament, 2024) mandates human-centric development and oversight of high-risk AI systems. Ensuring meaningful human control requires HMIs to provide operators with clear, actionable information to achieve SA at-a-glance, anticipate future states, and intervene when necessary. These regulations emphasize the need for carefully designed interfaces to support effective decision-making.

4.3. *The transition to ROCs*

Transitioning from onboard operation to ROC significantly changes the operator's role. Onboard operators retained in-situ skills and ship sense (Prison et al., 2013) by interacting with their environment and passengers, supporting heuristic decision-making. In ROCs, operators must rely entirely on HMI systems for information, altering their work environment, procedures, and cognitive processes. These shifts require investigation to ensure HMIs adequately support this new operational context.

4.4. *Human factors and readiness levels*

The early involvement of HF experts is essential to balance technical readiness levels (NASA, n.d.) and human readiness levels (ANSI/HFES, 2021). Addressing gaps between these dimensions ensures that HMIs are both technologically advanced and aligned with human needs and limitations (Johnsen & Aminoff, 2024).

4.5. *The expanded role of HMIs in ROCs*

HMIs in ROCs must go beyond basic monitoring and control to provide operators with all the information needed to project near-future scenarios (Madsen et al., 2024) and make prompt, informed decisions transparently. Designing interfaces that enhance SA, reduce cognitive load, and support high-pressure decision-making is essential for safe and effective remote operations.

4.6. *The need for context-specific solutions*

The findings of this study have significant implications for HMI design in autonomous ferry operations, both locally and internationally. The focus on automation transparency and cognitive workload management aligns with global trends in human-AI interaction research (He et al., 2022; Calvert et al., 2019). However, the unique challenges of maritime operations, such as the need for robust SA tools and effective communication with external stakeholders, underscore the importance of context-specific design solutions.

Future research should investigate the scalability of these findings to larger vessels and longer voyages. Additionally, exploring the integration of advanced technologies, such as AI-driven decision support systems and real-time hazard detection, will be crucial for enhancing operational safety and efficiency in diverse maritime contexts.

5. Conclusion

This study consolidates extensive research on HMI design for autonomous ferry operations, providing crucial insights into the challenges and opportunities of transitioning to remote operations. By applying a Human-Centred Design approach and utilizing the CRIOP methodology, the study emphasizes the importance of automation transparency, cognitive workload management, and compliance with industry standards to enhance operational safety and efficiency.

The findings contribute to the growing body of international research on human-AI interaction and establish a foundation for future advancements in this field. As autonomous ferry technology continues to develop, the lessons learned from this study will be instrumental in designing HMIs that ensure meaningful human control and support safe, reliable remote operations.

The milliAmpere2 trial highlighted the need for transparent and user-friendly HMIs to enhance operator comprehension and decision-making. The development of MF Estelle's HMI emphasized supporting SA and minimizing cognitive load. The CRIOP workshop reinforced the importance of HF integration and adherence to standards like IEC 63303 and OpenBridge to align HMIs with operator workflows and cognitive demands. Recommendations included improving automation transparency, refining alarm systems, and integrating tools like 360-degree displays and CCTV for real-time SA.

The transition to ROCs shifts operators' reliance entirely on HMI systems, requiring careful design to support new decision-making processes and environments. Ensuring mandated meaningful human control underscores the need for human-centric development.

HMIs in ROCs must provide operators with clear, actionable information to get SA at-a-glance and make timely decisions. Future work should focus on iterative testing, operator involvement, and aligning technical and human readiness to develop robust, user-focused systems.

Acknowledgement

This paper has been funded and supported by the Norwegian Research Council through the MAS project (no. 326676) and the SCAPE project (no. 327714).

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