解説
Explanation

Framework for Designing Reliable Propulsion Systems of Manned-autonomous Vessels *

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1. Introduction

The propulsion system of autonomous ships plays a pivotal role in their functionality, efficiency, and environmental impact. As the shipping industry shifts towards increased autonomy, a better understanding of current technologies, challenges, and potential future developments is crucial.

Nakashima et al. [1] proposed a model-based systematic design methodology and a safety evaluation method for autonomous ships. This was applied to the Designing the Future of Full Autonomous Ship (DFFAS) Project in Japan as a part of MEGURI2040 Fully Autonomous Ship Program launched by The Japan Foundation in 2020 to support the development of autonomous technologies [2]. The authors emphasized the importance of the Concept of Operation (ConOps) elements, which guide numerous stages from development and validation to the implementation of autonomous vessel systems.

Designing propulsion systems for autonomous ships is a complex task that requires a balance of efficiency, reliability, safety, and environmental impact. Many scholars highlight the importance of designing systems with built-in redundancy to mitigate the risk of system failure. Moreover, there is a consensus on the need for advanced monitoring and control systems, allowing remote diagnosis and fault prediction.

Further research is necessary to enhance the efficiency and reliability of both current and emerging propulsion technologies applicable to autonomous vessels. While many studies advocate for innovative propulsion systems and automation, fewer studies deal with overcoming the practical implementation challenges of incorporating an autonomous framework into a conventional vessel, a step often overlooked in the creation of full autonomy.

It is also crucial to note that autonomous does not mean unmanned. Even highly autonomous ships are likely to require some human crew for the foreseeable future. The transition to more autonomous shipping is expected to be gradual, and the impact on manning levels will depend on how the technology develops.

In the context of manned-autonomous vessels, the role of the human element stationed onshore becomes critical, yet under-explored, particularly in terms of controlling autonomous ships and supervising onboard personnel. A review by Veitch & Alsos [3] highlighted System-Theoretic Process Analysis (STPA) and Bayesian Networks (BNs) as the most suitable tools for goal-based design of safety controls. In the DFFAS project, the conceptual design of an autonomous navigation and operation system has been conducted using the Model-Based Systems Engineering MBSE approach.

However, to the best of the authors knowledge, these approaches are primarily used for high-level safety constraints and are mostly implemented for design of autonomous navigation systems, while the use of these approach for the design for propulsion system were less mentioned.

This study aims to introduce novel framework to be incorporated into design of propulsion system for manned-autonomous vessel. This includes considerations of marine engineers' work, functional risk assessment of machinery systems, and the role of the onshore fleet operation center, including its interaction with the vessel.

2. Safe manning for autonomous vessel

The Principles of Minimum Safe Manning [4], adopted in 2011, note that safe manning is a function of the number of qualified and experienced seafarers necessary for the safety and security of the ship, crew, passengers, cargo, and property, as well as for the protection of the marine

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environment. While this study is not dedicated to defining safe manning requirements for manned-autonomous vessels, the authors strongly believe that the evaluation of engine department work by Duration, Frequency, Competence, and Importance should always be the first step to consider and to embed into the design of the propulsion system for manned-autonomous vessels. This includes analyzing cases where work requires multiple people and where work overlaps. It then should become a reference for considering and maximizing the use of automation, remote control monitoring technology to be incorporated into ConOps.

In addition to IMO resolution A.1047(27), which recommends safe manning requirements for a manned-autonomous ship, a variety of other factors must also be considered. While the specifics may vary depending on the type and size of the vessel, its operational area, and the level of autonomy, the following points generally need to be addressed:

1. Level of Autonomy: The degree of autonomy or remote control applied on the different ship functions will be a major determinant of the crew size. Increased use of autonomy and remote control may require fewer crew members but also different competencies and more highly specialized personnel, on the ship as well as remote control/monitoring centers.
2. Transformation of Engineer’s Role: There may be a need for crew members with new skills, such as remote monitoring, cybersecurity, and system troubleshooting. As the nature of human roles onboard changes, this will affect how an engineer's competency and training should be planned.
3. Risk and Safety Analysis: Thorough risk assessment is necessary to understand how the autonomous systems might fail and what safety risks this could create.
4. System Redundancy: Level of redundancy built into the autonomous system affecting the need for human backup and shore supervision.
5. Regulations and Standards: Compliance and awareness of emerging and evolving regulations, such as the IMO MASS Code, as well as flag-state requirements.
6. Operational envelope: Factors such as routes, voyage duration, and the complexity of operations within the operational design domain.
7. Maintenance and Repair: Autonomous ships will still require maintenance and repair, and considerations should be made regarding how this should be performed.

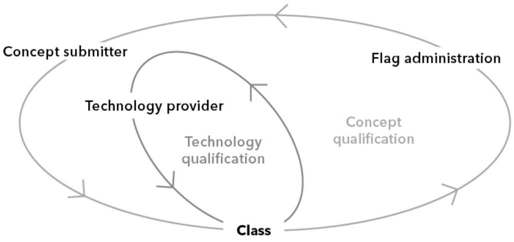


Fig.1 Process and Technology Guidance to the design and arrangements of systems supporting autonomous vessels (Image courtesy of DNV [5])

8. Technology Trustworthiness: It's crucial to ensure that the new technology employed in autonomous vessels is robust, reliable, including the incorporation of fail-safe mechanisms. One such mechanism is the concept qualification process proposed by DNV [5], as exemplified in Figure 1. This process ensures that the application of such innovative concepts and technologies results in a safety level equivalent to, or better than, that of conventional vessel operations.

3. Propulsion system specification and design flow

Evans [6] visualized the process of ship design as a spiral, representing a conceptual model of a process for effective ship design that has been widely adopted by shipyards worldwide. Similarly, the design of the propulsion system follows this iterative process from basic design to production, primarily consisting of three stages. The flow begins with defining functional requirements, which organize the operations and work of the engine department necessary for ship operation. In the basic design stage, the ship designer will design the equipment configuration required for operation, automation, remote control, and remote monitoring targets and specifications according to the specifications. Subsequently, a risk assessment will be performed to ensure that minimum safety equivalency is met in the event of various assumed anomalies with these specifications and workflows. Finally, these processes will be iterated several times until all the safety requirements can be satisfied.

On the other hand, the authors argue that a propulsion system for a manned-autonomous vessel requires additional design considerations. These include the incorporation of autonomous functions, remote control/monitoring systems (operable either from the engine control room or a shore operation center), and design interactions of new entities involved in the operation of the vessel.

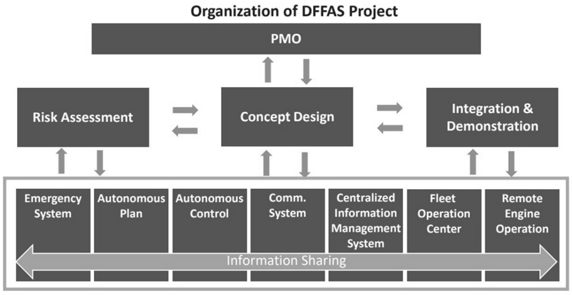


Fig.2 Organization of DFFAS project

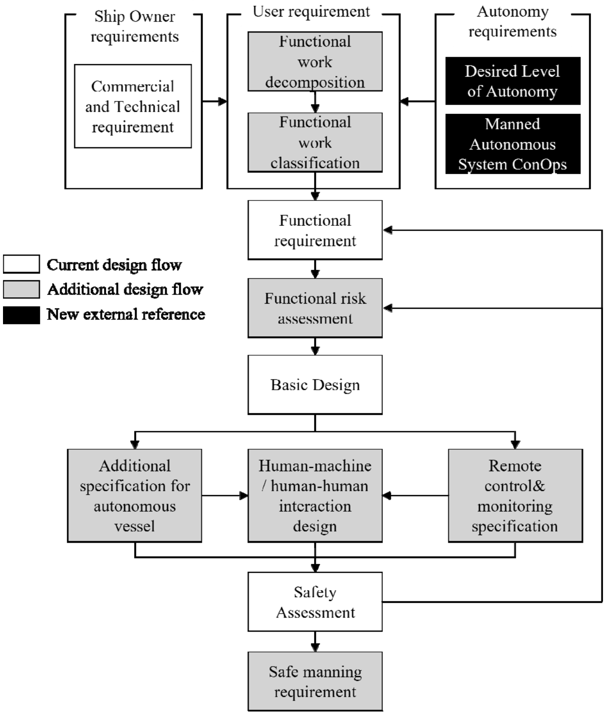


Fig.3 Proposed system design flow for propulsion system

In the previous DFFAS project, a container vessel named SUZAKU was retrofitted with an autonomous navigation and propulsion monitoring system to demonstrate the concept. At that time, there wasn't much room for introducing the novel concept of autonomy in propulsion, and emphasis was placed on the new role of shore engineers stationed at the Fleet Operation Center (FOC) tasked with supervising and supporting safe vessel operation with fewer engineers stationed onboard. In the next phase, termed as DFFAS+, a new container vessel will be designed and built. It will have more flexibility to introduce novel technologies or approaches in accordance with safe manning requirements, aiming to reach better or equivalent levels of safety compared to conventional vessels, especially in cases of onboard crew reduction objective.

We leveraged the advantages of having the DFFAS consortium, made up of approximately 60 cooperating companies and organizations, including 30 companies from diverse fields with the organization structure as shown by Figure 2. These include various original equipment manufacturers (OEMs), shipyards, and ship owners. Through the social implementation of the DFFAS project (referred to as DFFAS+), consortium members assigned to the propulsion working group conducted various workshops. They discussed and exercised the framework to consider overall requirements and functions based on the purpose and goal of the propulsion system as well as supporting remote monitoring functions and supervision at the FOC.

Through these workshops and discussions, a novel framework has been proposed and exercised for designing the propulsion system of a manned-autonomous vessel. In addition to conventional design stages, additional design flow depicted in Figure 3 were introduced in subsequent sub-sections:

3.1. Functional work decomposition

To better reflect user requirements, we have thoroughly organized the identification of the relationship diagram, which illustrates the work of marine engineers necessary to keep the propulsion system operational. We specifically referred to one methodology, Human-Centered Design (HCD). According to Veitch et al. [7], HCD effectively addresses safety-critical interactions between humans and machines using principles from ISO 9241 Part 210: Human-centered design for interactive systems. We concur that understanding and specifying the context-of-use for major functions in any shore control center should precede the definition of user requirements. This naturally implies that the context of use should be well-described in the Concept of Operations (ConOps). In this research, we designed the interactions of actors utilizing procedures, schemes, systems, tools, and means of communication to model interactions, as well as redundancy for both human-machine interaction onboard and sea-shore engineer's interaction. We identified several functional tasks that need to be considered for manned-autonomous vessels, which are as follows:

- Troubleshooting operations
- Scheduled maintenance work
- Spare parts and equipment inventory management
- Lubricant inventory management
- Fuel oil residual level management
- Fuel oil replenishment
- Engine plant preparation before departure

- Thruster operations (starting and shutdown)
- Auxiliary Engine (generator) operations
- Main engine shutdown
- Engine room fire detection and mitigation

One example of how interactions are being considered is illustrated in Figure 4, which pertains to relationship activity diagram for troubleshooting operations. A crucial point identified in the process is the importance of including the ship management company in the coordination loop, in addition to facilitating interactions between the onboard engineer and the shore engineer at the Fleet Operations Center (FOC). When multiple chief engineers are monitoring various vessels on duty at the FOC, it is advisable to have the supervisor from the ship management company responsible for a particular vessel, acting as the point of contact. This ensures efficient communication with the Original Equipment Manufacturer (OEM) or the ship operator/charterer regarding issues on each vessel.

3.2. Functional work/task classification

Understanding the interaction in each functional aspect of the newbuild manned-autonomous vessel allows for a clear perspective on user requirements, which can be linked to the design specifications of the propulsion system. Before progressing to the hardware/software design stage, another crucial step in the design process is to clearly derive these requirements from the decomposed functional work. For each functional work, the required level of autonomy and mandatory functions in the ConOps should be considered, allowing a more detailed work activity to be drawn. Through relevant discussions, and by referring to the manning plan desired by the ship owner as well as minimum safe manning principles, these activities were classified into functions requiring automation, onboard remote control, land remote control, land remote monitoring and supervision, and functions that will be maintained by manual operation.

As mentioned in Section 2, here, we consider an in-depth evaluation for the engine department's work using parameters such as Duration, Frequency, Competence, and Importance. Our aim is to maximize the use of automation, remote control, and land-based remote monitoring (and support) technologies for optimization. The top priority is to analyze cases where work requires multiple people and where work overlaps. Each function can then be broken down into a task list that includes the attributes listed below:

A) Task Duration:

Refers to the time required to execute each task. Time in this case is a measurement of total man-hours versus the actual duration taken for task completion. Since some tasks can be done in a shorter time by using multiple individuals, this work duration should ideally be minimized or kept the same.

B) Task Frequency

Refers to how often a task is performed, and should also be minimized or kept the same wherever possible.

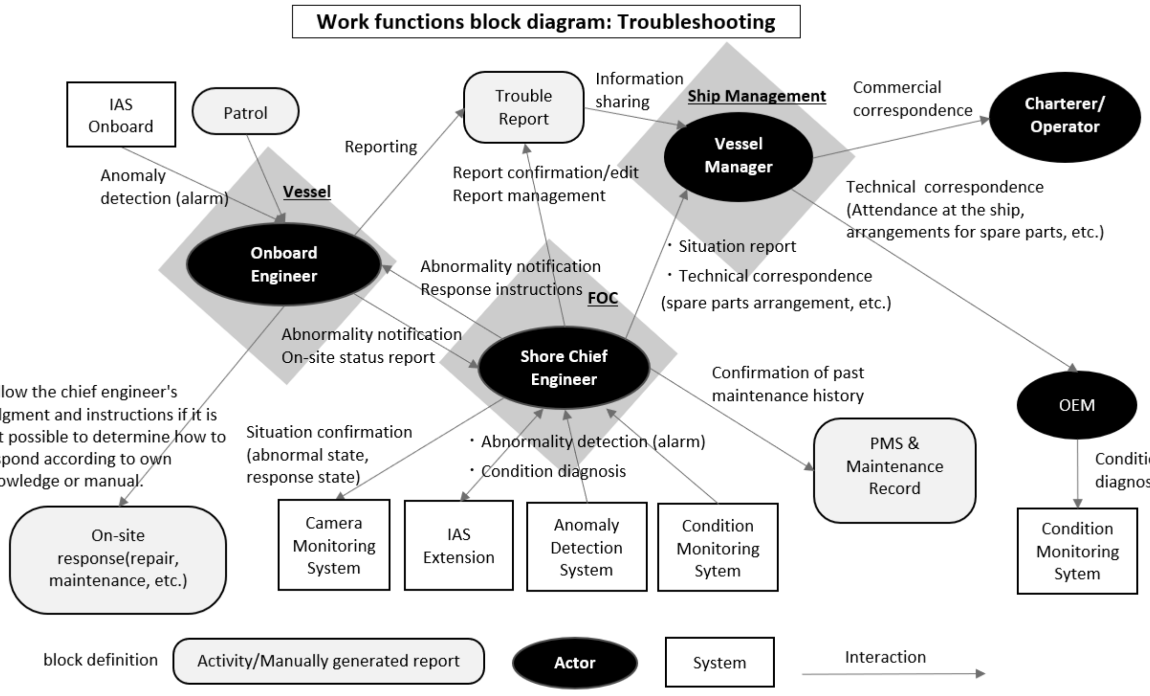


Fig.4 Example of a functional work decomposition for troubleshooting operation in manned-autonomous vessel operation

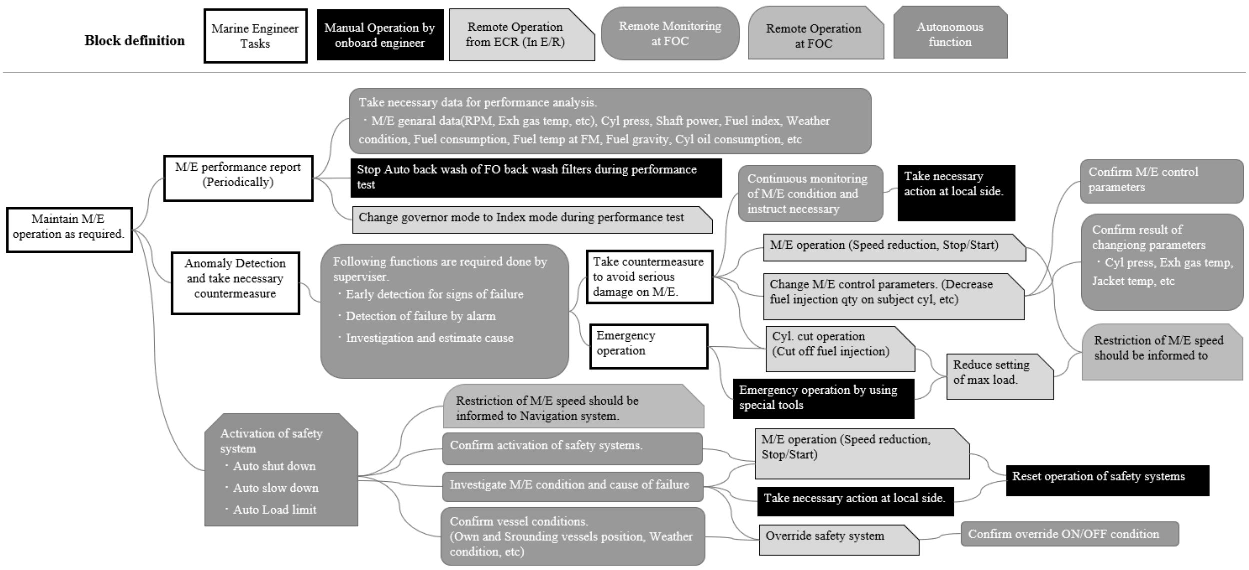


Fig.5 Example of a functional work classification of marine engineers onboard manned-autonomous vessel

C) Personnel competency

This includes the skills, training, and qualifications needed to consistently perform the task properly. At the very least, if the ship's engineer's capacity is insufficient, it will be supplemented by remote monitoring and technical support.

D) Task Importance

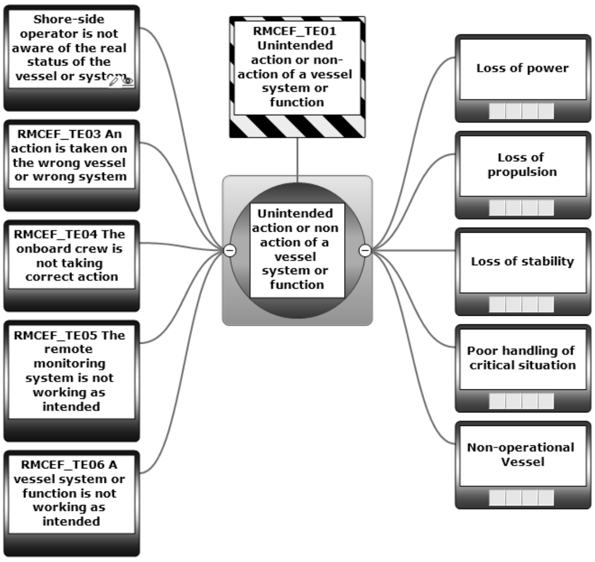
This involves the risk or consequence associated with improper performance when executing a task. As a measure, work associated with the risk of causing serious accidents should be closely monitored by onshore supervisors or covered by new automation functions to reduce the risk of trouble caused by improper operation as much as possible.

Understanding the task classification is beneficial for conveying user requirements more effectively during the process of defining functional requirements, especially in providing guidance for shipyards and OEMs. In this project we defined 224 tasks classified into 24 work classifications. Figure 5 exemplified tasks necessary for M/E Operation.

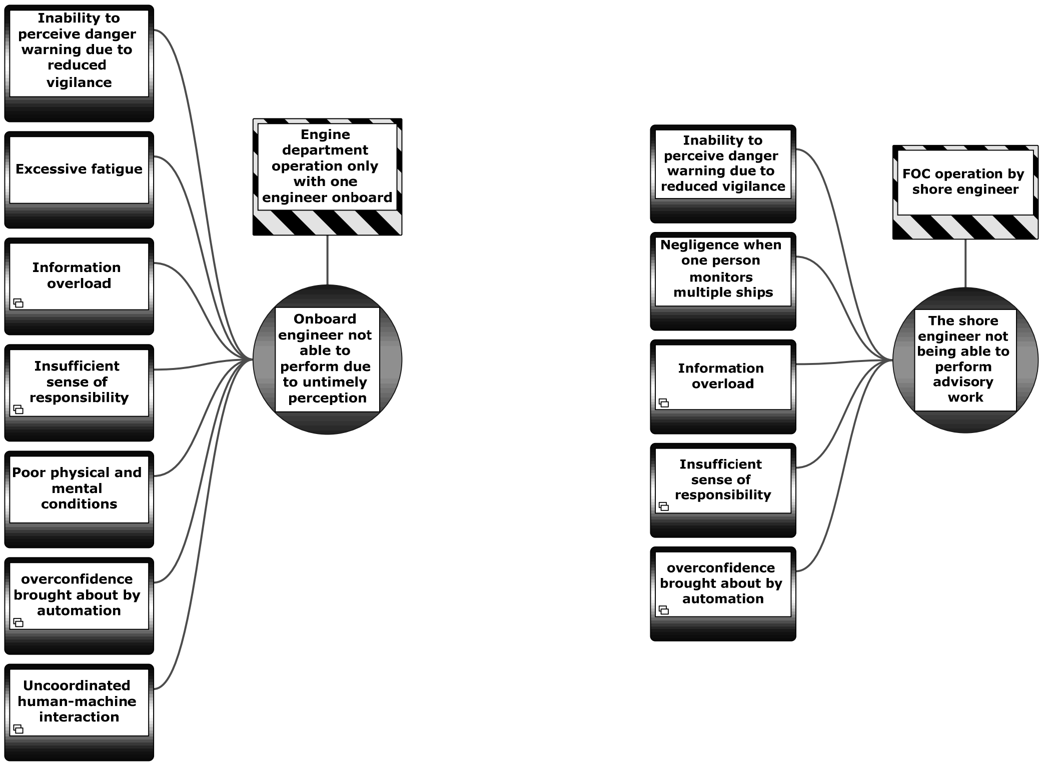
3.3. Basic Hazard Identification:

By formulating task classifications, we can easily identify tasks that require the introduction of novel or supporting technologies/tools. This process results in a more focused approach towards targeted tasks that necessitate a thorough functional risk assessment. The aim is to identify hazards in propulsion system operation that derive from the Concept of Operations (ConOps) requirements. In DFFAS+, we utilize the bow-tie methodology [8] to perform this stage, as exemplified in Figure 6. During this process, we referred to Class guideline DNV-CG-0264 [5] for guidance on safely implementing novel technologies in autonomous vessel functions.

We discuss and agree on high-level prevention measures for each threat and mitigation barriers for each potential consequence. As a result, three distinct risk categories are associated with the manned-autonomous vessel propulsion system when considering the use of novel technology. These include risks associated with ship operation with only one engineer onboard (as aimed by DFFAS+), work supervision by a shore engineer, and the use of a remote control /monitoring system. Each bowtie diagram consists of a hazard, an unsafe condition described as a top event, and a set of threats and consequences related to the event.



(a) Bowtie showing threats for remote control/monitoring system for manned-autonomous vessel



(b) Bowtie showing threats for operation with one engineer onboard (c) Bowtie showing threats for remote supervision by shore engineer

Fig.6 Example of basic hazard identification by bow-tie methodology

For each threat, we identify barriers that will be used to prevent the threats from leading to the top event. Similarly, for each consequence, we identify barriers to recover from the occurrence of the top event, and to prevent major consequences from happening. As experienced in the project, identifying these barriers is central to the functional safety assessment and has proven invaluable in allowing focused and detailed safety analysis of each part of the system.

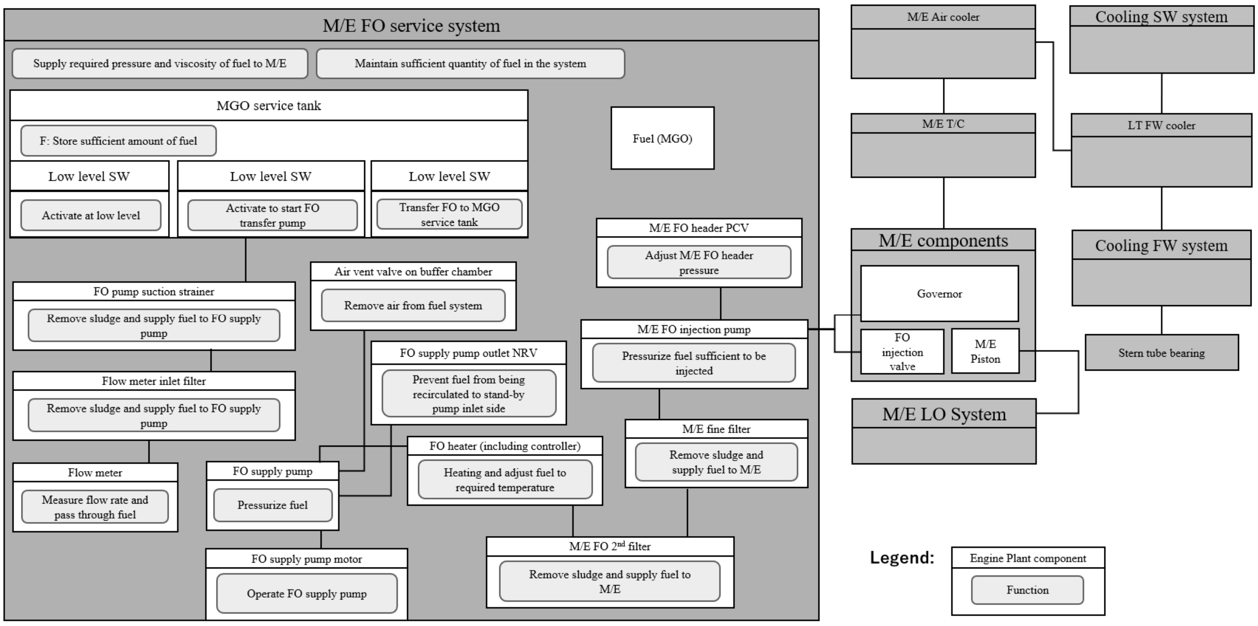
The DFFAS+ project has been contributing to a draft class guideline developed by DNV for the approval of REMC (Remote Engineering Monitoring and Control) systems, focuses on remote operations of machinery and other engineering systems. The guidelines are based on practical risk analysis, as experienced in several projects, including DFFAS+.

3.4. Functional safety assessment

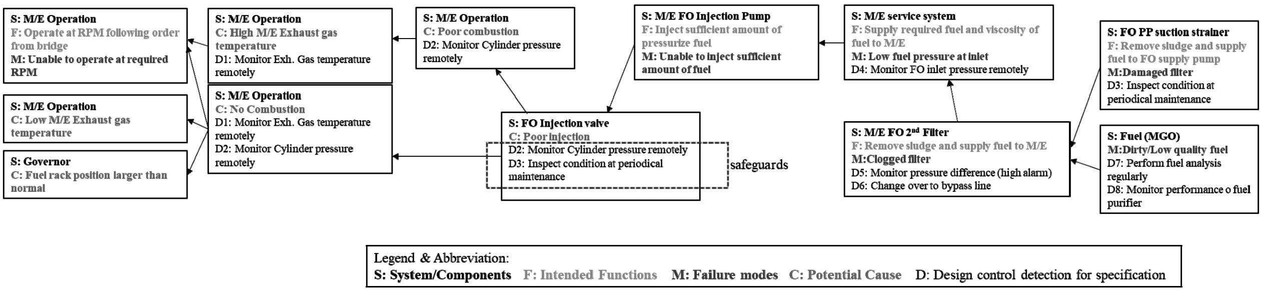
This process involves identifying the failure modes of the equipment that comprises the engine system, performing FMEA (Failure Mode and Effects Analysis) and FTA (Fault Tree Analysis), selecting the measurement items necessary for status diagnosis and anomaly detection, and developing the equipment status diagnosis logic. Model-Based Safety Assessment (MBSA) was selected as the methodology, and Ansys Medini™ Analyze [9], a model-based toolset for functional safety design and analysis, is being utilized. The following systematic steps were undertaken:

A) Creation of the block diagram describing component, system, and functions in engine plant (Figure 7(a)).
B) Define functions and the potential malfunctions for each component, which configure the main systems.
C) FMEA to be done according to the defined malfunctions (failure modes).
D) Evaluation of failure modes and identification of design control detection as well as safeguards

In conducting FMEA, various failure modes with differing causes and effects were outlined, and each failure mode was evaluated using "Occurrence" and "Detection" for potential failure causes, and "Severity" for potential failure effects. There may be a close connection between tasks, and subsequently between failure modes. Thus, connections between failure modes of different systems can be made and visually identified. Figure 7(b) exemplifies a functional block diagram, showing the connections between different failures in M/E operation that may share common causes and effects. Finally, safeguards can be designed for each system component.



(a) Relationship diagram of various systems in functional block diagram (emphasize on FO service system)



(b) Failure propagation flowchart connecting different failure mode scenario and identification of safeguards

Fig.7 Functional safety assessment

Table 1 Additional sensor specification design following functional safety assessment

Criticality	Functions	Component / Function	Potential Failure Mode	Potential Effect of Failure	Potential Cause(s)	Current Design Controls Detection
A	B	C	D	E	F	G
Very High	M/E to be operated at required RPM by following bridge order	Stern Tube bearing	Damaged bearings	Unable to be operated at required RPM	Insufficient supply of sea water to S/T	S/T sea water inlet press is monitored remotely by IAS
		Reverse M/E rotation	Not able to reverse M/E rotation		Low LO press for clutch	Reduction Gear LO inlet pressure is monitored remotely and low pressure is noticed by alarm
High	M/E to be operated at required RPM by following bridge order	M/E Operation	High Exh. gas temp		High scavenging air temperature	A/C air outlet temperature is monitored remotely by IAS
			No combustion		Low scavenging air pressure	Scav air pressure is monitored remotely by IAS
	M/E Operation in all operation mode		High Scav air temp	Exh gas temp is high	High temperature of intake air	A/C air inlet temperature is monitored remotely by IAS
			No combustion	Low M/E Exh gas temp	Poor injection	Cylinder pressure is monitored remotely
Medium	Supply sufficient qty and suitable temp of sea water to cool down cooling fresh water and stern tube lubrication	Pressurize and supply sea water to coolers and stern tube	Unable to pressurize and discharge sufficient quantity of sea water	Insufficient amount of sea water being circulated	Sufficient quantity of sea water cannot be taken in	Condition of sea water intake of sea chest is inspected by UWI
	Cool down LT fresh water	Supply sufficient quantity and suitable temp of sea water to cool down cooling fresh water and stern tube lubrication	Unable to supply sufficient quantity of sea water to sea water system	Fail to cool down LT fresh water	Insufficient pressure or quantity of sea water	Cooling sea water pump inlet/outlet pressure is monitored remotely by IAS

Note: text marked in red in column G represent required sensor to be placed for control detection to be performed

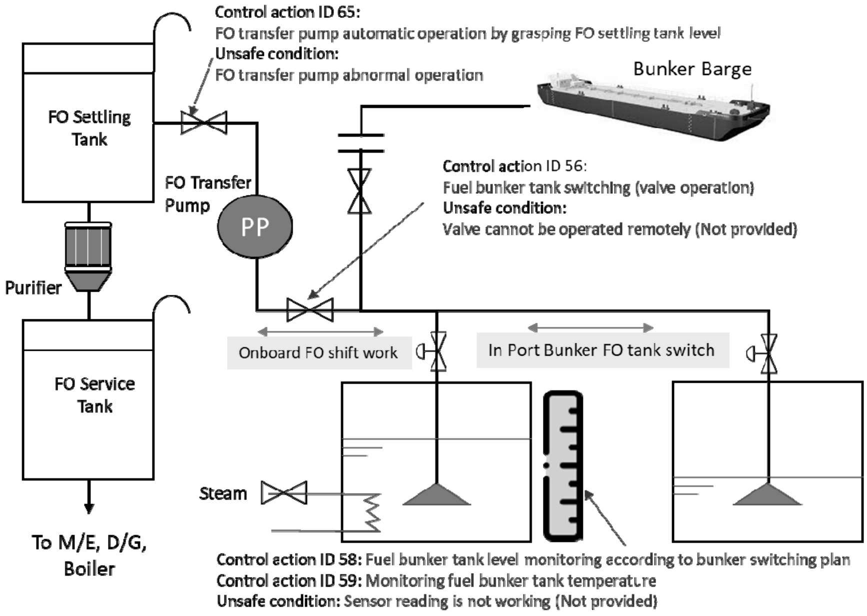


Fig.8 Identification of unsafe condition (example of onboard fuel shift work)

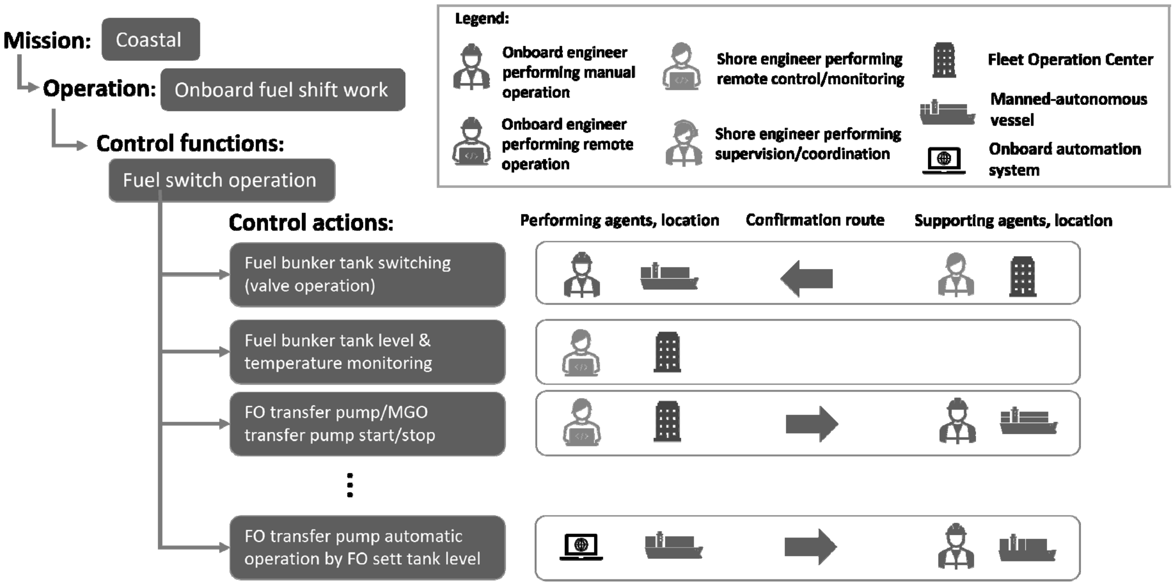


Fig.9 New system requirement to support coordination between onboard and shore engineer

3.5. Additional specification for autonomous vessel

Following the basic design discussions with the shipyard and OEMs regarding propulsion system specifications, control detection measures, and safeguard functions to support the monitoring of critical machinery functions, we utilized this information extensively to propose sensor specifications for installation on the newbuild vessel. Moreover, we delineated how telemetry data capture from these sensors should be linked to either the Integrated Alarm System (IAS) or other systems designed for both onboard and shore monitoring. Table 1 illustrates how the results of functional safety assessments are used to determine the required sensors for monitoring functions

The sensor specifications devised are fundamental to the operation of the monitoring scheme and safeguards. However, they may not provide complete visibility for all operations. In this context, we link the Failure Mode and Effects Analysis (FMEA) to the identification of unsafe conditions in the hazard analysis. Figure 8 illustrates an instance of an unsafe condition that could occur during onboard fuel shift works. This iterative process, focused on critical operations, enables us to determine whether the designed condition monitoring scheme can identify or mitigate unsafe conditions.

3.6. Remote control and monitoring specification

Since the Fleet Operation Center (FOC) is a new organization in the operation of manned-autonomous vessels, we have also discussed and determined the design of workflows and systems for remote monitoring, operation, and management by a land-based supervisor (equivalent to a chief engineer). This includes the nature of communication between the ship's engineer and the shore engineer stationed at the FOC, as well as interaction to automation system.

Figure 9 illustrates how the tasks should be performed and supervised for specific operation in a mission phase. These considerations subsequently dictate the new functions and systems needed to support this operational design. To this end, a Concept of Operations (ConOps) for Remote Engine Monitoring and Control (REMC) of Autonomous Vessels was specifically created as part of the ship-systems ConOps. At the time of this manuscript's publication, the ConOps is being iteratively modified and reviewed by the classification society for concept qualification.

In advancing this objective, we describe a general concept of manning, the remote engine monitoring center, and the operational structure extracted from the DFFAS's REMC ConOps in the sections below:

Target of the REMC

The REMC aims to enable onshore monitoring of multiple vessels to ensure their continued safe operation by a single engineer aboard each vessel.

Key Success Factors

The remote control and monitoring system at the FOC should empower shore engineers to effectively supervise the engine plant from ashore, thereby decreasing the workload of the onboard engineer. While monitoring the condition of the main engine is a crucial part of the engineer's duties, a system that can lessen these responsibilities is also necessary for maintaining vessel operation with fewer engineers compared to existing conventional vessels.

General Operational Strategy

Team of shore engineers, working in shifts, will be assigned the task of remote monitoring and supervision of the fleet under their purview. For the DFFAS project, the FOC intends to oversee the operation of five manned-autonomous vessels operating domestically within Japanese waters.

We propose that the monitoring concept needs to be tested before implementation. An advantage we seek to capitalize on is for ship owners who already have remote monitoring systems in place for health and performance propulsion systems for conventional vessels, such as [10]. This is a context in which various assumptions and hypotheses can be verified. Specifically, the practical challenges associated with remote operation center personnel managing multiple vessels effectively are a crucial factor that needs to be more thoroughly tested, rather than merely conceptualized.

3.7. Safe manning evaluation

In the final process, a qualitative and quantitative evaluation shall be conducted to assess the volume of work and to determine whether labor savings can be achieved in the ship's engine department. This will constitute the final assessment, carried out together with the flag state agency, confirming whether the minimum safety equivalent can be met with a reduced number of onboard personnel on a manned-autonomous vessel equipped with onboard automation, supplemented by supervision and backup from shore personnel.

While the DFFAS project is not designed to recommend a generic safe manning requirement for a manned-autonomous vessel (a bottom-up approach), the proposed framework serves as a valuable tool to be used for designing the propulsion system of a manned-autonomous vessel. This is particularly true when considering how the propulsion system should be designed to meet the user's manning requirements (a top-down approach), identifying potential challenges, and systematically proposing solutions to meet these requirements.

4. Contribution of this research

Clear motivation underlying the introduction to the proposed framework, are classified, and discussed below:

A) Response to Seafarer Shortage:

We aim to design an efficient propulsion system with fewer engineers onboard for Japanese domestic vessels, in response to the shortage of seafarers in Japan.

B) Improved Safety of Ship Operation

Due to concerns that fatigue and other factors may cause humans to overlook dangerous conditions, leading to poor judgment, the development of an automated system and remote-control supervision is essential. These will assist in safe operations and reduce human error.

C) Reduction of Workload on Onboard Seafarers

The use of an onboard automated control system, combined with the ability to perform remote control from a Fleet Operations Center (FOC), can significantly reduce the watchkeeping workload for onboard engineers.

D) Contribution to International Standardization

Active efforts are anticipated in the development of more concrete rules for the societal implementation of technologies developed for autonomous vessels. This operational concept will strengthen initiatives already emerging in maritime industries and contribute to the development of international rules related to remote control and engine room monitoring for autonomous vessels.

E) Contribution to the Legal System

By defining and implementing the framework, we can showcase a proposal for the flag state and classification society in a creating safe manning requirement for engine room operations in accordance with the competence, qualifications, and training required for the seafarers who will man the autonomous vessels.

5. Conclusion

This paper introduces a novel framework to be incorporated into the design of propulsion systems for manned-autonomous vessels, as experienced in the DFFAS project. The proposed framework significantly incorporates user requirements by defining the critical tasks of onboard engineers. Moreover, the application of functional safety analysis is highlighted, leading to comprehensive additional specifications. These specifications are intended for both onboard automation and remote control/monitoring systems, ensuring safety levels equivalent to, or better than, those of conventional vessel operations, especially in scenarios where reduced crew members are desired to operate the autonomous vessel. The proposed method is believed to be scalable, offering insights on how the propulsion system design should adapt to meet varying user manning requirements at different levels of autonomy.

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