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DESIGN AND CHALLENGES OF AN AUTONOMOUS SHIP ALARM MONITORING SYSTEM FOR ENHANCED MARITIME SAFETY

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Abstract. *Maritime transportation holds the largest share of global trade, but the rising operational costs - particularly those associated with human resources - pose significant challenges to the industry. Coupled with this, the shortage of skilled seafarers and the prevalence of human error, which accounts for 59.1% of maritime accidents, threaten the sector's sustainability. The shift towards autonomous ships presents a promising alternative for enhancing operational efficiency and safety while reducing reliance on onboard human crews. Autonomous vessels, controlled remotely by shore-based engineers, require robust systems for effective and safe operation. One critical component of such systems is the autonomous ship alarm monitoring system, essential for managing the complex array of alarms that ensure the safety and functionality of ship operations. This paper examines the challenges posed by the increasing complexity of ship control systems and the necessity of enhanced automation. Through an in-situ study across various merchant ships, the criticality and response time of alarms were evaluated, leading to a structured approach for engineer responsibilities and response strategies. The findings contribute to a proposed concept for an efficient, autonomous alarm management system, addressing both technical and operational needs to support maritime sustainability.*

Keywords: autonomous ship, alarms monitoring system, maritime safety, remote operation

PROJEKT I WYZWANIA AUTONOMICZNEGO SYSTEMU MONITOROWANIA ALARMÓW NA STATKU DLA ZWIĘKSZENIA BEZPIECZEŃSTWA MORSKIEGO

Streszczenie. *Transport morski stanowi największy udział w handlu światowym, jednak rosnące koszty operacyjne – zwłaszcza te związane z zasobami ludzkimi – stwarzają poważne wyzwania dla branży. Dodatkowo, niedobór wykwalifikowanych marynarzy oraz powszechność błędów ludzkich, które odpowiadają za 59,1% wypadków morskich, zagrażają trwałości sektora. Przejście na statki autonomiczne stanowi obiecującą alternatywę, która może zwiększyć efektywność operacyjną i bezpieczeństwo przy jednoczesnym zmniejszeniu zależności od załóg pokładowych. Statki autonomiczne, sterowane zdalnie przez inżynierów z lądu, wymagają solidnych systemów zapewniających ich skuteczne i bezpieczne działanie. Jednym z kluczowych elementów takich systemów jest autonomiczny system monitorowania alarmów, niezbędny do zarządzania złożoną siecią sygnałów alarmowych gwarantujących bezpieczeństwo i funkcjonalność operacji statku. Niniejszy artykuł analizuje wyzwania wynikające z rosnącej złożoności systemów sterowania statkami oraz konieczność zwiększenia poziomu automatyzacji. Na podstawie badań in-situ prowadzonych na różnych statkach handlowych oceniono krytyczność i czas reakcji na alarmy, co pozwoliło na opracowanie podejścia strukturalnego do obowiązków inżyniera oraz strategii reakcji. Wyniki te przyczyniają się do propozycji koncepcji wydajnego, autonomicznego systemu zarządzania alarmami, odpowiadającego zarówno na potrzeby techniczne, jak i operacyjne, wspierając tym samym zrównoważony rozwój sektora morskiego.*

Słowa kluczowe: statek autonomiczny, system monitorowania alarmów, bezpieczeństwo na morzu, zdalna obsługa

Introduction

Maritime transportation plays a vital role in global trade, accounting for the largest share of the movement of goods across the world’s oceans. The continuous operation and safety of conventional ships (CS) rely on an array of interconnected systems and equipment, including main engines, auxiliary engines, and various support systems. Maintaining these systems at peak performance necessitates ongoing maintenance by qualified crew members who are stationed on board. However, recent statistics from 2014 to 2022 reveal that human error is the predominant factor in maritime incidents, responsible for 59.1% of accident events and contributing to 67.6% of overall incident causes. System and equipment failures account for another significant portion, underscoring the dual challenges of human error and mechanical reliability. [4]

At the same time, the maritime industry is facing a shortage of qualified seafarers as younger generations are increasingly less inclined to pursue careers at sea, driven by the desire for a more stable social life and closer connections to family and friends. This social shift presents a looming challenge for the maritime sector, threatening its sustainability and operational efficiency.

In response to these challenges, the concept of autonomous ships has emerged as a viable alternative, aiming to reduce human presence on board while ensuring safe and efficient operations through remote management by shore-based engineers. The shift to autonomous vessels represents a transformative change in the maritime environment, significantly impacting operational procedures, safety protocols, and the overall management of ship systems. Among the critical systems requiring adaptation is the alarm monitoring system, which must be robust enough to manage a wide range of potential issues that could compromise the ship’s safety or functionality.

This study focuses on developing an effective autonomous ship alarm monitoring system, addressing the increased complexity of control systems and the critical need for efficient, real-time responses. By evaluating alarms based on criticality and required response times, this research proposes an innovative concept for managing alarms and establishes a structured duty framework for engineers overseeing multiple ships remotely. Through a detailed assessment of real-world cases and the development of response management scenarios, this work contributes to the broader goal of achieving safe and reliable remote operations for autonomous ships, paving the way for sustainable advancements in maritime navigation.

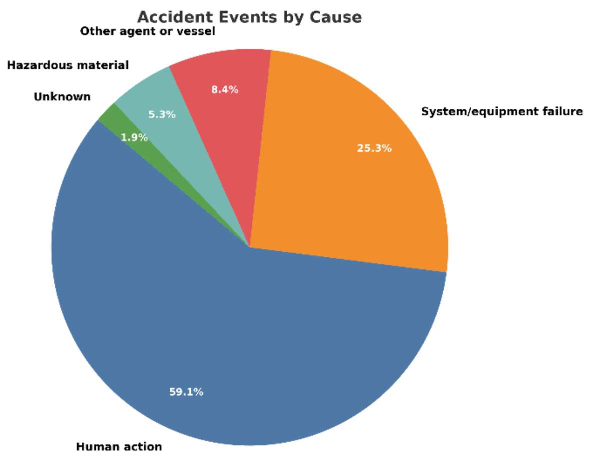

Fig. 1. Percentage of accident events for the period 2014–2022, categorized by accident event types [4]

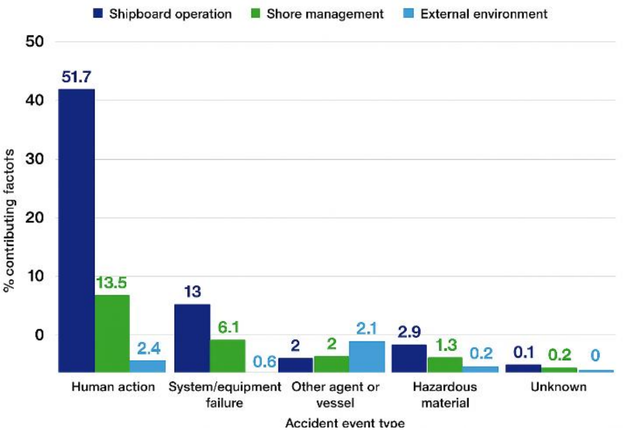

Fig. 2. Percentage of contributing factors for the period 2014–2022, categorized by contributing factor types and accident event types [4]

Numerous studies have shown that young people are no more motivated and attracted to work at sea and sail with ships. This is due to the increasing need to be close to family, friends and take profit of nice social life. This social phenomenon will soon cause a lack of qualified maritime human resources capable to operate ships worldwide. The implementation of autonomous ship may be considered as one of alternative solution to assure maritime industry sustainability. The introduction of this type of ship in the maritime environment will face several challenges. One the challenges is the increase of level of automation and safe remote control. In this work, a study, and assessments of alarms onboard in term of criticality and response time were cried out, resulting in the proposal of engineers responsibility structure and a concept of how a failure will be approached depending of its criticality and availability of an engineer to take care.

1. Literature review

The topic of ship systems alarm monitoring and remote control has garnered significant attention from researchers over the years. Various studies have explored innovative solutions and approaches to enhance the efficiency and reliability of these systems. Ruddianto et al. [7] conducted experimental research that resulted in a simple, cost-effective, and efficient engine alarm system tailored to facilitate economical maritime transportation [7]. Similarly, Tawiah et al. [10] introduced a practical, affordable, and reliable online engine control room device monitoring system, leveraging PLCs and SCADA-based technology while adhering to essential design requirements [10]. Qi et al. [6] proposed an engine room alarm system that utilized a program based on PLC and SCADA, developed using TIA Portal software to achieve a comprehensive monitoring solution [6]. Xue et al. [11] utilized MATLAB/Simulink to design and simulate a monitoring and alarming interface for ship power systems, showcasing the potential of simulation tools in developing advanced monitoring mechanisms [11].

Further advancements include Dagkinis et al. [3], who presented an innovative control system designed to regulate and adjust operational conditions across modern ship functions. This system developed optimal strategies for sensors within the Ship Integrated Control System (SICS), focusing on preventive maintenance and repair actions [3]. Kang et al. [5] introduced a hierarchical-level fault detection and diagnosis (HL-FDD) method that integrated ship engine domain expertise with sophisticated data analysis techniques for enhanced fault management [5]. Yang et al. [12] proposed a comprehensive three-phase framework combining Systems-Theoretic Process Analysis (STPA), state machines, and Sequentially Timed Events Plotting (STEP) to identify potential failure scenarios during control mode transitions in autonomous ships [12]. Størkersen et al. [9] provided a detailed study that culminated in numerous recommendations to be considered for the safe deployment of remotely controlled vessels [9].

Over recent years, experts in maritime operations have conducted extensive research to ensure the safe and efficient implementation of autonomous ships, with many findings presented at international conferences [1,2,8]. Despite the breadth of research, no comprehensive studies have been found that directly address the specific issue of alarm monitoring systems for autonomous ships, highlighting the unique contribution of this study.

2. Material and methodology

The data collection is based on an in-situ study carried out on board of numerous merchant ships of different types. For each ship visited, the alarms system monitoring, engine logbook, electrical drawings were studied, and engineers were interviewed. Experienced cases, lessons learnt, were assessed. Criticality and response time of each alarm were evaluated. At the first stage of this study, following assumptions are considered to facilitate the initial concept of the system:

- The fleet to be monitored remotely consists of 12 ships that are trading worldwide.
- The ships are of same types (Bulk carrier) and are sisters: Same building drawings, same alarms' monitoring systems.
- Cargo onboard does not need any condition remote monitoring.
- Ship-shore communication is reliable and engineers on duty have continuous remote access to ships' systems.
- 3 Shore control centres are installed in different locations to cover time-zoon: India- Morocco-America.
- Alarms rising Scenarios are limited to one watch (4 working hours).
- The embarked intelligent technology is not able to resolve the problem autonomously and remote human intervention is needed from the shore control center.
- Staff at the SCC is qualified and satisfactorily equipped to intervene efficiently.

3. Result

3.1. Alarms criticality and response time evaluation

The ship systems' alarms were analyzed in terms of criticality and response time, with the findings summarized in table 1. These results are drawn from an in-situ study, comprehensive interviews with experienced engineers, and the authors' extensive expertise in the maritime field. This study provides valuable insights for prioritizing high-risk alarms that are critical for ship safety, equipping engineers on duty with the necessary knowledge to respond effectively and efficiently. By addressing equipment faults in a timely manner, this approach helps mitigate the risk of system failures and operational downtime, ensuring uninterrupted and safe vessel operations.

3.2. Engineers' duty and responsibility structure

Figure 3 illustrates the structured distribution of engineers' duties and responsibilities. According to this framework, each 3rd Engineer is assigned to monitor and control four ships, while each 2nd Engineer oversees six ships, and a Chief Engineer manages a group of 12 ships. This strategic allocation streamlines the staffing model, resulting in a reduction of 11 Chief Engineers, 10 2nd Engineers, and 9 3rd Engineers, significantly cutting operational costs and minimizing the likelihood of human errors. By optimizing the engineer-to-ship ratio, this structure supports more efficient management of ship operations, enhancing both performance and safety in a cost-effective manner.

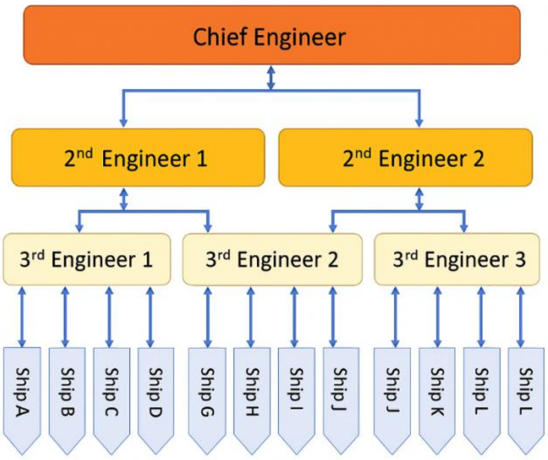

Fig. 3. Engineer responsibility structure for ship monitoring

3.3. Alarms response management scenarios

The presented alarm response management scenarios outline how engineers respond to incoming alarms based on the risk level and complexity of the required intervention.

Scenario No. 1

When Ship A sends an alert, the 3rd Engineer 1 remotely checks the alarm monitoring system, which displays alarm code MA02, indicating low criticality. The system algorithm provides the engineer with potential solutions, leveraging pre-programmed data and past learnings. Using the available technology and personal expertise, the engineer successfully resolves the issue, restoring the system to normal operational status.

Scenario No. 2

Ship A sends an alert, prompting the 3rd Engineer 1 to check the remote alarm monitoring system. The displayed alarm code is ME03, categorized as medium criticality. The system algorithm suggests various solutions for the engineer's consideration. The engineer begins working on the issue. Ten minutes later, Ship B sends a warning alert with alarm code ML43, also of medium criticality. The engineer must decide whether to continue addressing the initial problem or shift focus to the new alert, depending on the progress made. Delays in resolving medium-critical alarms could escalate them to high criticality. In this scenario, both issues are assumed to be resolved without requiring additional support.

Scenario No. 3

Ship A triggers an alert, and the 3rd Engineer 1 reviews the system remotely at time t=0, identifying alarm code ME03 with medium criticality. The system proposes several potential solutions. While working on this problem, Ship B sends an alert after 10 minutes, displaying code ML43 with medium criticality. The engineer must prioritize between the two alerts. At 15 minutes from $t = 0$, Ship C sends a high-criticality alert (ML01). Recognizing the urgency, the engineer shifts attention to resolving this high-risk issue immediately. Once the critical alarm is addressed, the engineer resumes working on the medium-priority problems, successfully restoring all systems to normal operation.

Scenario No. 4

In this scenario, Ship A sends an alert at $t = 0$, prompting the 3rd Engineer 1 to identify alarm code ME03 with medium criticality and begin addressing it. Ten minutes later, Ship B sends an alert for alarm code ML43, also at medium criticality. The engineer must decide whether to continue with the first task or switch to the second based on progress. After 15 minutes from $t = 0$, Ship C sends an alert with alarm code ML01, classified as high criticality. The engineer immediately prioritizes this critical alert. Two minutes later, Ship D sends an alert with alarm code GA10, another high-criticality issue. The system autonomously assesses the situation and escalates it to the 2nd Engineer No. 1, who takes over handling Ship D's issue. With the coordinated support of the 2nd Engineer, all issues are resolved, restoring normal operations.

Scenario No. 5

Ship A issues an alert at t=0, prompting the 3rd Engineer 1 to identify alarm code ME03 with medium criticality and start addressing it. Ten minutes later, Ship B sends an alert for alarm code ML43 (medium criticality). The engineer weighs the progress on the first issue before deciding to switch focus. After 15 minutes, Ship C sends a high-criticality alert (ML01), which the engineer prioritizes. Shortly after, Ship D sends a high-criticality alert (GA10). The system autonomously signals the 2nd Engineer No. 1 to assist with Ship D. Delays in resolving the initial medium-criticality alarms (ME03 and ML43) elevate them to high criticality. The system escalates these to the Chief Engineer, who steps in to assist in addressing the unresolved alarms. Ultimately, all issues are assumed to be resolved, restoring ship systems to their normal function.

3.4. The algorithm for managing alarm responses

The alarm response management algorithm outlines how engineers should react to alarms based on risk level and complexity. The process is divided into three key steps:

Step 1

The algorithm first checks for any incoming alarms and identifies which ship the alert is from, as shown in figure 4. The first step in the alarm response management process begins with continuous monitoring for incoming alarms. The flowchart illustrates how the system evaluates and allocates alarms based on the ship group to which they belong:

a. **Start monitoring for alarms**: The system is initialized and actively checks for any incoming alarm signals.

b. **Alarm group allocation**:
  - The system checks if the alarm originates from ships in the group **A–D**. If the alarm is detected in this group, it moves to the next step to **check the alarm type**.
  - If the alarm is not in **A–D**, the system checks whether it is in the second group, **E–H**. If found, it proceeds to determine the alarm type.
  - If no alarms are detected in **E–H**, the system finally checks for incoming alarms in **I–L**. If the alarm is from this group, it moves forward to analyze the alarm type.

c. **Outcome**: This step ensures that any detected alarm is quickly identified and categorized according to its ship group, streamlining the response protocol by determining which engineer or control team should be notified based on the group assignment.

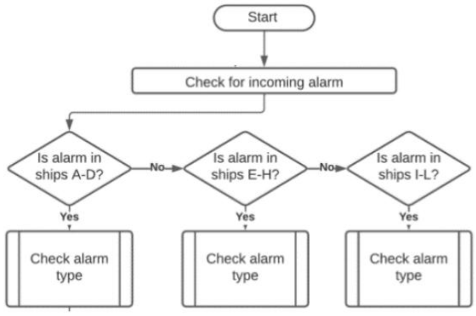

Fig. 4. Initial alarm detection and ship group allocation algorithm

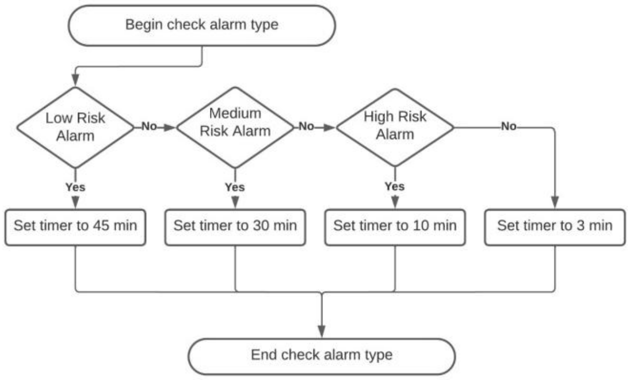

Fig. 5. Alarm type evaluation and timer setting algorithm

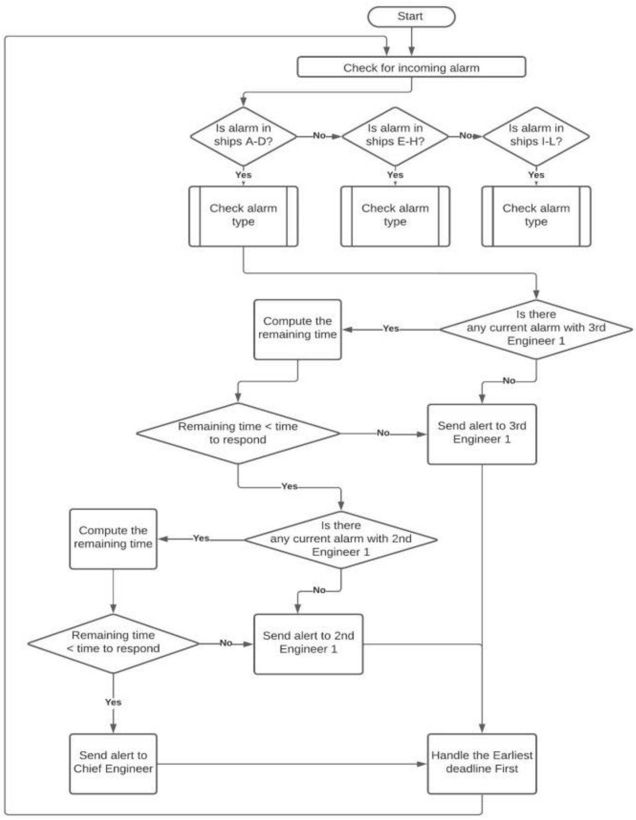

Fig. 6. Alarm response allocation algorithm for 3rd Engineer 1

Step 2

This step involves checking the type of alarm that has been identified and setting an appropriate response timer based on its risk level. The flowchart breaks down the process as follows (figure 5):

a. Begin alarm type evaluation: The system starts by categorizing the detected alarm based on its risk level.

b. Risk level assessment:
- **Low risk alarm**: If the alarm is classified as low risk, the system sets the response timer to **45 minutes**, allowing for less immediate action as it poses minimal risk to the ship's operation.
- **Medium risk alarm**: If the alarm is categorized as medium risk, the system sets the response timer to **30 minutes**. This ensures a quicker response than a low-risk alarm but does not demand the same urgency as a high-risk alarm.
- **High risk alarm**: If the alarm is deemed high risk, the system sets the response timer to **10 minutes**, emphasizing the need for prompt action due to the significant threat to ship safety.
- **Unknown or undefined alarm type**: If the alarm type does not match any predefined categories, the system sets a default timer to **3 minutes** to prompt immediate attention until the type is further evaluated.

c. End of alarm type check: Once the timer is set according to the risk level, the system concludes the alarm type evaluation and prepares for the next step in the alarm response process.

Step 3

In this stage we have three main algorithms, each assigned to a different engineer

Algorithm dedicated to 3rd Engineer 1: overview and workflow

This flowchart illustrates the decision-making process for managing incoming alarms and allocating responsibilities to 3rd Engineer 1 (figure 6). The algorithm ensures that alarms are prioritized and addressed efficiently based on current workload and risk level.

a. Start and initial alarm check: The system begins by checking for any incoming alarms and determines which group of ships (A–D, E–H, or I–L) the alarm originates from. Once identified, the alarm type is evaluated to establish its risk level (low, medium, or high).

b. Compute remaining time: The system calculates the remaining time available before the response time deadline is reached for the identified alarm. This is crucial for prioritizing tasks and ensuring that high-risk alarms are attended to promptly.

c. Check engineer availability:
- **3rd Engineer 1's current workload**: The system checks if 3rd Engineer 1 is currently engaged with other alarms.
  - **If not busy**: The alert is sent directly to 3rd Engineer 1 for handling.
  - **If busy**: The system assesses whether the remaining time for the new alarm is less than the time required for response.

d. Response time comparison:
- **If the remaining time is adequate**: The system continues to monitor the situation to ensure the alarm can be addressed within the required timeframe.
- **If the remaining time is insufficient**: The system moves to check if 2nd Engineer 1 is available for handling the alarm.

e. Escalation to other engineers:
- **If the 3rd Engineer's workload exceeds capacity**: The system sends the alert to 2nd Engineer 1 or, if necessary, escalates further to the Chief Engineer based on current availability and priority.
- **Alert management**: If 3rd Engineer 1 is occupied, the system re-evaluates the workload and shifts responsibility as needed, ensuring that no alarms are overlooked or delayed.

f. Priority handling: If multiple alarms are present, the system uses an "earliest deadline first" approach to handle alarms in order of urgency, ensuring that alarms with the shortest response time remaining are prioritized.

Algorithm dedicated to 3rd Engineer 2: overview and workflow

This flowchart demonstrates the decision-making process for handling alarms, specifically assigned to 3rd Engineer 2. The algorithm is designed to ensure efficient alarm management and response prioritization. As can be shown in figure 7.

a. **Initial alarm detection**: The system continuously checks for any incoming alarms and identifies which group of ships (A–D, E–H, or I–L) the alarm originates from. Once identified, the system proceeds to evaluate the type of alarm and its urgency.
b. **Compute remaining time**: After determining the alarm type, the system calculates the remaining time before the response deadline for the alarm.
c. **Check current alarms with 3rd Engineer 2**:
   - The system checks if 3rd Engineer 2 is currently addressing any alarms.
     - **If not busy**: The alert is sent directly to 3rd Engineer 2 for immediate handling.
     - **If busy**: The system computes whether the remaining time for the new alarm is less than the required time for response.
d. **Evaluate response time**:
   - **If remaining time is sufficient**: The system continues monitoring to ensure the alarm can be managed within the allowed timeframe.
   - **If remaining time is insufficient**: The system proceeds to check if 2nd Engineer 2 or 2nd Engineer 1 is available to handle the alarm.
e. **Escalation process**:
   - **Check for current alarms with 2nd Engineer 2 and 2nd Engineer 1**: The system checks if either 2nd Engineer is currently handling an alarm.
     - **If 2nd Engineer 2 is available**: The alert is assigned to 2nd Engineer 2.
     - **If 2nd Engineer 1 is available**: The alert is sent to 2nd Engineer 1 if 2nd Engineer 2 is also occupied.
   - **Compare response time for escalation**: The system evaluates which 2nd Engineer has a shorter remaining time and sends the alert accordingly.
   - **If all engineers are busy and remaining time is short**: The alert is escalated to the Chief Engineer for immediate attention.
f. **Handle the earliest deadline first**:
   - If multiple alarms are present and require attention, the system prioritizes them based on the "earliest deadline first" principle. This ensures that the most urgent alarms are addressed first to prevent escalation.

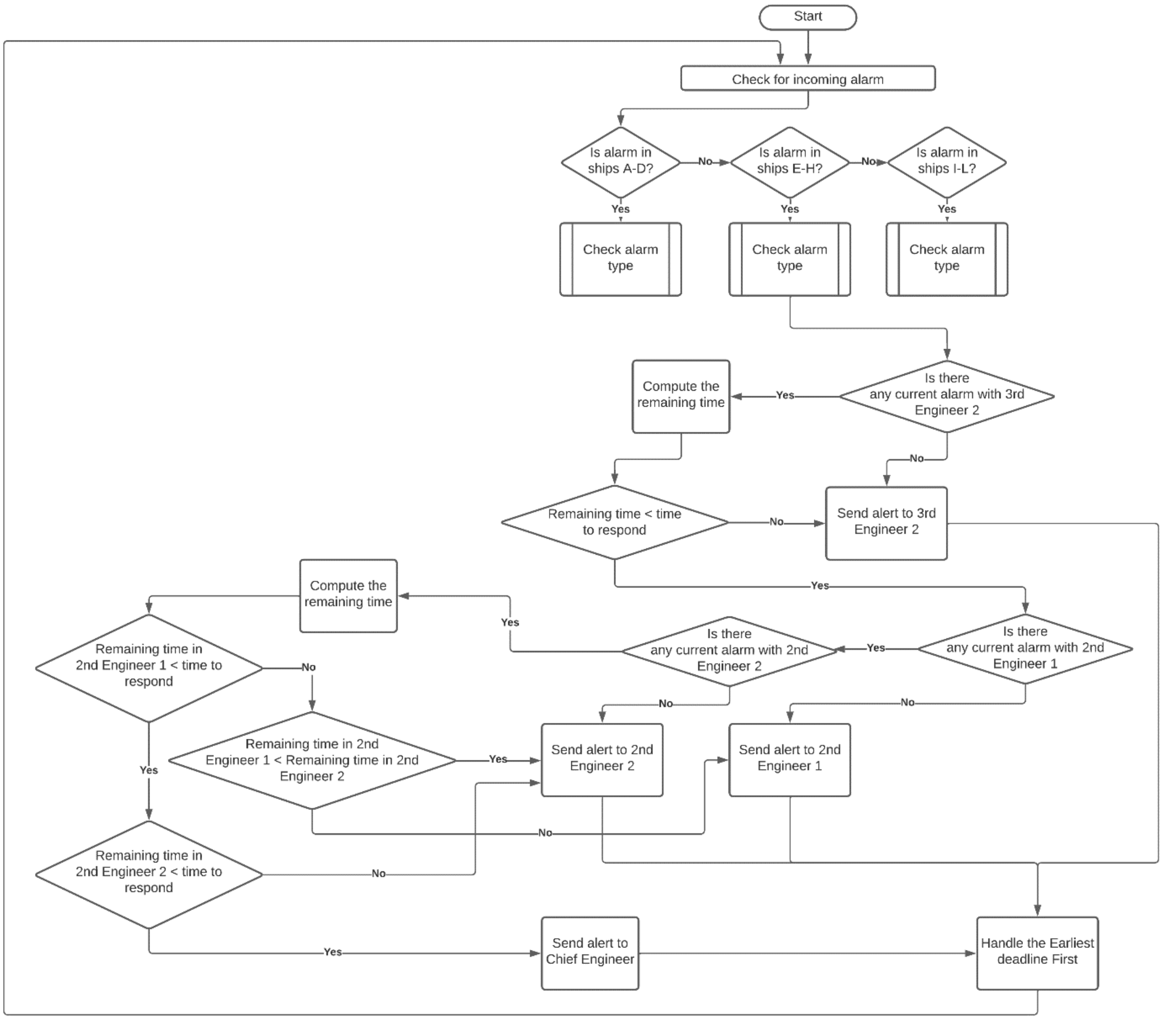

Fig. 7. Alarm response allocation algorithm for 3rd Engineer 2

Algorithm dedicated to 3rd Engineer 3: overview and workflow

This flowchart outlines the decision-making process for alarm management, specifically designed for 3rd Engineer 3. The algorithm is focused on efficient allocation and response prioritization to maintain system safety and operational efficiency. As can be shown in figure 8.

a. **Start and initial alarm check**: The system begins by checking for any incoming alarms and identifying which group of ships (A–D, E–H, or I–L) the alarm originates from. Once detected, the system checks the type of alarm to determine its urgency.

b. **Compute remaining time**: After identifying the type of alarm, the system calculates the remaining time available before the response time deadline is reached.
c. **Check current alarms with 3rd Engineer 3**:
   - The system checks if 3rd Engineer 3 is currently handling any active alarms.
     - **If not busy**: The alarm is assigned to 3rd Engineer 3 for immediate response.
     - **If busy**: The system calculates whether the remaining time for responding to the new alarm is less than the set response time.
d. **Evaluate remaining response time**:
   - **If the remaining time is adequate**: The system continues monitoring the situation to ensure that 3rd Engineer 3 can address the alarm within the required timeframe.
   - **If the remaining time is insufficient**: The system checks if 2nd Engineer 2 is available to take over the response.
e. **Escalation process**:
   - **Check for current alarms with 2nd Engineer 2**: The system verifies whether 2nd Engineer 2 is managing any active alarms.
     - **If 2nd Engineer 2 is available**: The alert is redirected to 2nd Engineer 2 for handling.
     - **If not available**: The system escalates the alert to the Chief Engineer if response times become critical.
f. **Compare response time for escalation**:
   - The system calculates and compares response times between 2nd Engineer 2 and other potential responders to prioritize who should receive the alert.
g. **Handle the earliest deadline first**:
   - If multiple alarms are present, the system prioritizes them using the "earliest deadline first" approach to ensure that the most urgent alarms are handled promptly.

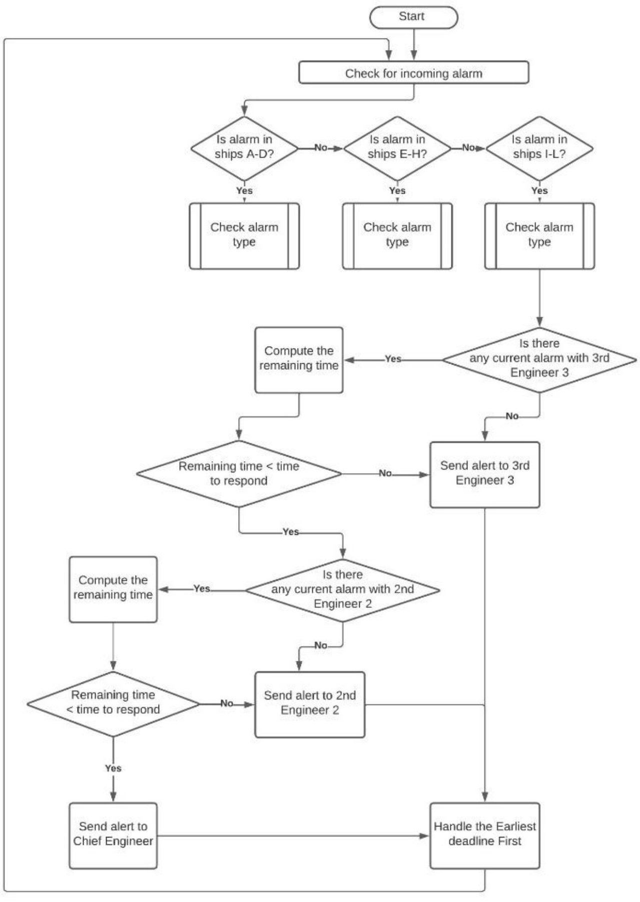

Fig. 8. Alarm response allocation algorithm for 3rd Engineer 3

4. Discussion

The combined algorithms dedicated to 3rd Engineer 1, 3rd Engineer 2, and 3rd Engineer 3 showcase an integrated approach for managing alarms on autonomous ships. Each algorithm is structured to ensure efficient allocation of tasks and prioritization based on the risk level and urgency of incoming alarms. The workflows begin with initial checks to identify the ship group and alarm type, followed by calculations of the remaining time for response. This allows for dynamic and adaptive decision-making to allocate the alarm to the most appropriate engineer. If the primary engineer is occupied or the time for response is insufficient, the system strategically escalates the task to the next available engineer, including the 2nd Engineers and, when necessary, the Chief Engineer. The algorithms incorporate real-time workload assessments, response time calculations, and escalation protocols to optimize the management of multiple alarms and maintain operational safety. The “earliest deadline first” approach ensures that the most critical alarms are prioritized, minimizing risks associated with delayed responses. Overall, the results indicate that this layered, algorithm-based approach enhances the efficiency and reliability of alarm management in an autonomous ship environment. By distributing tasks based on engineer availability and response urgency, the system effectively minimizes human error, reduces operational downtime, and improves the safety and reliability of ship operations. This comprehensive structure provides a robust foundation for managing complex alarm scenarios and ensures a coordinated response strategy across all engineering levels.

5. Conclusion

The development of an advanced alarm monitoring system for autonomous ships represents a pivotal advancement towards fully unmanned maritime navigation. This innovative concept addresses the distinctive challenges posed by ship autonomy, ensuring continuous, real-time monitoring of critical systems and rapid, coordinated responses to potential emergencies. By integrating advanced technologies such as artificial intelligence, the Internet of Things (IoT), and state-of-the-art communication systems, this solution aims to enhance the safety, reliability, and operational efficiency of autonomous vessels, positioning them as a sustainable option for the future of maritime transport. Nevertheless, achieving this vision requires sustained efforts in research and development, alongside the establishment of comprehensive standards and regulations that govern the use of alarm monitoring systems within the context of autonomous navigation. The path forward calls for a collaborative approach that unites maritime industry stakeholders, regulatory bodies, and research institutions to bridge technological advancements with robust governance frameworks. Through such partnerships, the maritime sector can advance toward an era where autonomous ships safely and efficiently traverse the world’s oceans, setting new benchmarks for innovation, safety, and sustainability.

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