APPROACHES TO REAL-TIME MENTAL FATIGUE AND COGNITIVE LOAD ASSESSMENT IN MARITIME OPERATIONS VIA RGB VIDEO ANALYSIS

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Introduction. Maritime transportation remains a cornerstone of the global economy, facilitating over 80% of international trade. Maritime operators, particularly navigators and captains, bear significant responsibility for the safe and efficient execution of navigational tasks in complex and unpredictable conditions [1]. However, mental fatigue, increased cognitive load, and stress are constant risks that can lead to reduced performance, errors, and even catastrophic consequences.

Statistics indicate that the human factor is the primary cause of over 75% of maritime accidents. For instance, the collision between the container ship ACX Crystal and the destroyer USS Fitzgerald in 2017 highlighted the role of crew fatigue as a contributing factor. Similarly, the collision of the USS John S. McCain with the tanker Alnic MC in the same year was partially attributed to human error and fatigue. These tragic events underscore the critical need to monitor the mental state of seafarers to prevent similar incidents in the future [2].

Despite significant advancements in fatigue and workload monitoring technologies, existing methods have substantial limitations. Most current systems rely on expensive and invasive physiological sensors such as electroencephalography (EEG), electrocardiography (ECG), and electromyography (EMG), as well as subjective assessments using scales like the Karolinska Sleepiness Scale (KSS) or the Fatigue Severity Scale (FSS). Such approaches are not always practical for continuous onboard use due to the high cost of equipment, operational complexity, and discomfort for the crew.

The relevance of this research becomes evident in the context of the need for safe and efficient maritime operations. Developing an objective, non-intrusive, and cost-effective system for monitoring mental fatigue and workload is critically important. Utilizing RGB video stream analysis to track physical indicators of fatigue—such as posture, head position, and eye closure frequency—opens new possibilities for creating practical solutions that can be easily integrated into existing ship systems.

Practical examples confirm the necessity of this approach. Imagine a vessel undertaking a prolonged ocean crossing, where the crew works in shifts under challenging weather conditions. Traditional monitoring methods may be unavailable or ineffective in such situations. In contrast, a system that analyzes video streams from bridge cameras can assess the seafarers' condition in real time without infringing on their privacy or adding additional burdens.

Furthermore, international maritime organizations like the International Maritime Organization (IMO) increasingly emphasize the importance of the human element in navigational safety [3]. Implementing a monitoring system based on video analytics can be a significant step toward fulfilling recommendations and standards aimed at minimizing risks associated with human factors.

The importance of this research lies in its potential to significantly enhance the safety and efficiency of maritime operations through the implementation of an innovative approach to monitoring the mental state of the crew. The proposed system is non-intrusive, cost-effective, and scalable, making it suitable for various types of vessels and operational conditions.

The necessity of this study is also reinforced by the growing complexity of maritime operations and the increasing workload on crews due to automation and reduced personnel numbers [4]. Timely detection of signs of fatigue and stress will help prevent errors, optimize task distribution, and ensure adequate rest for seafarers.

Practical examples include:

- Preventing Accidents: Implementing the system can help avoid incidents similar to the

2017 collision between the ACX Crystal and the USS Fitzgerald, where crew fatigue was considered among the causes.

- Improving Efficiency: In areas of intense navigation, such as straits or near ports, the system can alert operators to overload, allowing for duty redistribution or providing additional support.

- Supporting Crew Well-being: Continuous monitoring will facilitate timely detection of stress signs, positively impacting the morale and overall health of seafarers.

Therefore, this research aims to address the urgent challenge of enhancing the safety and efficiency of maritime operations through an innovative and practical approach to monitoring mental fatigue and workload. The proposed system has the potential to become a vital tool in the maritime industry, contributing to the reduction of risks associated with human factors and improving the overall level of safety at sea.

Analysis of previous research. The paper, [5] «Detecting Mental Fatigue in Vessel Pilots Using Deep Learning and Physiological Sensors», focuses on detecting Mental Fatigue in vessel pilots through deep learning models using EEG and ECG data. The study involved 6 trained maritime pilots from the Brazilian Navy, aged 19–48, who completed a 60–90-minute harbor navigation task in a ship simulator. The physiological sensors included a 14-channel EEG headset (Emotiv Epoc+, 128 Hz) and an ECG monitor (Electrocardiogram Sensor PRO, MySignals). Fatigue assessment was based on the Karolinska Sleepiness Scale (KSS) before and after each task. The Convolutional Neural Network (CNN) achieved the highest accuracy for Single-Subject Classification, reaching 89–96%, while Cross-Subject Classification achieved 82% validation accuracy but required further refinement for broader applications.

The paper, [6] «A Decentralized Sensor Fusion Approach to Human Fatigue Monitoring in Maritime Operations», proposes a decentralized sensor fusion system to monitor human fatigue in maritime settings. The study employed a range of physiological sensors, including EEG, ECG, EMG, thermometer, and eye tracker and the goal was to classify fatigue levels on the Karolinska Sleepiness Scale (KSS). Only 4 participants in the study navigated a simulated ship in a narrow canal at 22 knots to induce fatigue over more than 1 hour. The system used CNN classifiers to process individual sensor data, followed by a 5-layer Fuzzy Neural Network (FuNN) for final decision fusion. Results demonstrated a high classification accuracy, reaching 96.08% with centralized fusion and maintaining 88.42% even with partial sensor data. The study implements a novel neural network architecture and achieves great results, but again fails to provide a practical solution to measuring fatigue.

The follow-up, [7] «Investigating an Integrated Sensor Fusion System for Mental Fatigue Assessment for Demanding Maritime Operations», follows a similar technical setup (EEG, ECG, EMG, body temperature, and eye tracker) with a slightly higher sample of 11 participants and similarly used Karolinska Sleepiness Scale (KSS); however, it proposed a sensor fusion data preparation approach that allowed for an accuracy increase of up to 99%. These studies prove that Mental Fatigue is measurable with high accuracy in a maritime context. However, the technological setup proposed might not be feasible for implementation in real-world scenarios. The price of the equipment and its comfort for daily use are the main barriers to the implementation.

The authors of the [8], «ADTIDO: Detecting the Tired Deck Officer with Fusion Feature Methods», proposed using Reaction Time the navigator took stirring action to measure Mental Fatigue. The study used EEG and derived eyelid closure (ECD) as inputs to the Bidirectional Gated Recurrent Unit (Bi-GRU) and included 21 participants. The model achieved a high accuracy of 95.74% in classification into alert, middle, and fatigued states. This work provides a unique approach to objectively measuring fatigue by using Reaction Time; however, still relies on the expensive sensor for measurements.

The authors of [9], «A Model for Forecasting Mental Fatigue in Maritime Operations», investigated predicting future states of Mental Fatigue. They combined physiological data (EEG and ECG sensors) with external factors (ship motion and noise levels, etc.) and used a Long Short-Term Memory (LSTM) neural network to forecast the future state of MF on the Karolinska Sleepiness Scale (KSS). The study involved 20 participants and achieved an accuracy of 87%. This study proposes a unique combination of physiological data and external factors to forecast mental fatigue, but once again fails to provide a practical technological solution.

The paper [10], «EEG-Based Driver Fatigue Monitoring within a Human–Ship–Environment System: Implications for Ship Braking Safety», measures Mental Fatigue based only EEG features: power spectral entropy and centroid frequency and uses a simpler Ridge Regression Model. The study also uses a slightly different fatigue scale – the Fatigue Severity Scale (FSS), but not the less subjective measure of fatigue. The authors reported a strong correlation (r=0.83) between predicted and actual FSS scores. Overall, this study demonstrates that a basic technical setup and a simple model can still achieve equally high results.

«Exploring Seafarers Workload "Recognition Model with EEG, ECG, and Task Scenarios" Complexity», [11] assesses Mental Workload in maritime operators using a dual-sensor setup: EEG and ECG (NeuroSky Mindwave and Polar V800 watch) and various machine learning models (Decision Tree, KNN, SVM, Naive Bayes, Bagging) to classify high and low workload levels. 23 participants navigated scenarios with varying complexities, from normal conditions to emergencies, to induce different workload levels. The Bagging algorithm achieved the highest accuracy of 92.5% with an AUC of 96.0%. This study strengthens the idea that simple machine learning algorithms can perform equally well with novel approaches such as deep learning.

The paper [12], «Mental Workload Assessment Using Eye-Tracking Glasses in a Simulated Maritime Scenario», investigates Mental Workload (MW) in maritime officers by tracking eye movements during a navigation simulation. The study included 20 seafarers (mean age 34.6) in the MaRiSa simulator at the World Maritime University, simulating typical coastal traffic conditions. Participants wore Tobii Eye-Tracking Glasses (sampling at 30Hz), which recorded their fixations and transitions between key instruments (e.g., ECDIS, ARPA, and console). Taskload varied between 5 minutes of easy navigation, 10 minutes of hard conditions, and another 5 minutes of easy conditions. Eye movement data were analyzed using the Nearest Neighbour Index (NNI) to detect changes in fixation distribution, indicating workload shifts. The study found that the NNI was generally higher when transitioning from low to high task load, supporting its potential as a workload indicator. This study provides an outlook that uses a completely different set of sensors, compared with other studies that relied on EEG, ECG, body temperature, etc. can have similar results and accuracy.

The paper, [13] «Emotional State Evaluation during Collision Avoidance Operations of Seafarers Using Ship Bridge Simulator and Wearable EEG», explored the link between Emotional States and different navigational scenarios. The study included 11 seafarers performing collision avoidance tasks in a ship bridge simulator. Each participant wore a 14-channel Emotiv EEG headset (sampling at 128 Hz) to capture brainwave data, focusing on valence (positive-negative) and arousal (calm-excited). Two navigational scenarios were designed: a simple two-ship encounter and a complex multi-ship encounter in a confined waterway. Using these EEG-derived features, an SVM (Support Vector Machine) model classified emotional states, achieving an accuracy of 82% in distinguishing between positive and negative emotions. Results showed that positive emotions were more frequent during simple navigational tasks, while negative emotions predominated in complex scenarios, indicating stress and higher cognitive load.

In [14], «EEG-based Mental Workload and Stress Monitoring of Crew Members in Maritime Virtual Simulator», authors investigated Mental Workload and Stress in varying roles among the crew changing responsibility levels from officer to captain. 7 participants performed tasks wearing a 14-channel Emotiv EEG headset sampling theta, alpha, and beta waves which were further divided into 4 levels and classified by using autoencoder and SVM achieving an accuracy of 79.9% for 4 levels and 95.4% when reduced to predicting 2 levels. This study solidifies the notion that simpler technical setup in this case only EEG headset and basic machine learning algorithm can achieve good classification results.

Main Part of Research. To summarize, studies on fatigue, workload, and stress monitoring in maritime operations have achieved important advancements. Multi-sensor fusion systems, such as those combining EEG, ECG, EMG, body temperature, and eye tracking, have significantly improved the accuracy of detecting cognitive states, achieving up to 99% accuracy in some cases. Machine learning models, particularly CNNs and SVMs, have also refined prediction capabilities, enabling robust classification across different cognitive states with high precision. Additionally, researchers have effectively utilized simulated and VR-based environments to replicate maritime tasks, allowing safe, controlled assessments of cognitive load in complex scenarios. These achievements collectively underscore the potential of real-time fatigue and workload monitoring, offering insights that could be crucial for enhancing crew performance, safety, and well-being in maritime operations.

However, despite these strides, current methods rely predominantly on expensive, intrusive equipment and subjective scales like the Karolinska Sleepiness Scale (KSS) and Fatigue Severity Scale (FSS). While effective in controlled studies, these approaches present challenges for practical, real-world implementation, underscoring the need for a non-intrusive, affordable alternative suitable for continuous, real-time use in maritime settings.

Proposal. This proposal aims to overcome the limitations of current fatigue and workload detection methods by developing an objective, real-time monitoring system based on RGB video stream analysis. By tracking indicators such as posture, head position, and eye closure, this approach offers a non-invasive, cost-effective alternative to sensor-dependent systems. RGB video analysis has the potential to integrate seamlessly into existing maritime training and onboard monitoring systems, making it viable for implementation on ships of varying sizes and operational environments.

Research Objectives and Structure. The research will be structured into three main areas, each addressing critical aspects of the system’s development and deployment.

Technological Solution Optimization. This phase will focus on identifying the most cost-effective and practical technological setup for real-world maritime applications. Experiments will test both single-camera and multi-camera configurations to determine optimal coverage and data accuracy across different vessel sizes and layouts. Additionally, this stage will evaluate whether to use GPU-intensive algorithms such as Convolutional Neural Networks (CNNs) or simpler, less resource-intensive machine learning models like Support Vector Machines (SVMs), based on their performance in detecting fatigue indicators within video streams. The goal is to balance computational efficiency with detection accuracy.

Feature Selection and Integration with Onboard Data. The second research sector will explore a multi-feature approach to accurately detect fatigue and workload by combining key physiological indicators, including eye closure frequency, head tilt, gaze direction, and body posture. This phase will investigate how these visual indicators correlate with known fatigue markers, ensuring reliable detection. Furthermore, the project will examine how to enhance these video-based insights by integrating external data available onboard, such as weather conditions, sea state, and ship telemetry (e.g., speed, and engine state). The integration of these environmental factors will improve the model's adaptability and provide context-sensitive fatigue and workload insights.

Conclusions. *Development of Objective Measures for Mental Fatigue, Workload, and Stress.*The final research component will focus on defining and testing objective measures of mental fatigue, workload, and stress that are practical for real-world application. Instead of relying on subjective feedback from crew members or invasive physiological monitoring, this phase will investigate reaction time to navigational commands and visual attention metrics as proxies for the cognitive load. By analyzing delays in executing commands, the system can provide real-time indicators of cognitive strain and alertness. This approach aims to deliver reliable mental workload assessment without additional equipment or subjective measures, making it scalable across diverse maritime settings.

Expected Impact. This project envisions creating a scalable, real-time fatigue and workload monitoring system that is accessible, non-intrusive, and deployable on various vessel types. By leveraging affordable RGB video analysis, the proposed system could become a critical tool in enhancing crew safety, improving operational efficiency, and proactively managing mental fatigue and workload in demanding maritime environments.

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