Jurnal Teknik Mesin, Industri, Elektro dan Informatika
Volume 5, Nomor 3, September 2026
e-ISSN: 2963-7805; p-ISSN: 2963-8208, Hal. 199-215
DOI: https://doi.org/10.55606/jtmei.v5i3.6404
Tersedia: https://ejurnal.politeknikpratama.ac.id/index.php/jtmei

Implementation of Facial Landmark Method on Smart BNWAS Integrated ESP32 VDR

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Abstract. Fatigue among bridge watchkeepers is a major contributor to maritime accidents caused by human error, particularly on non-conventional vessels that lack active safety systems and voyage data recording devices. Conventional Bridge Navigational Watch Alarm Systems (BNWAS) remain passive and rely on manual interaction, limiting their effectiveness in detecting actual operator drowsiness. Furthermore, the high implementation cost of standard Voyage Data Recorders (VDR) restricts their adoption on smaller vessels. This study proposes a Smart BNWAS integrated with an ESP32-based VDR subsystem to provide active fatigue monitoring and structured voyage data recording at a lower cost. An experimental approach with a prototyping development model was employed, including system design, implementation, integration, and performance evaluation under controlled laboratory conditions. Operator alertness was monitored using MediaPipe Face Mesh through Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR) analysis executed on a Raspberry Pi 5, which also functioned as a web server for real-time monitoring. System performance was evaluated through alarm response testing, fatigue detection experiments, web dashboard functionality assessment, and VDR data logging verification. Experimental results demonstrated a 100% detection success rate across ten predefined laboratory test scenarios and successful recording of timestamp, positioning, and orientation data in CSV format. The proposed Smart BNWAS-VDR system provides a low-cost maritime safety platform with fatigue detection, adaptive data logging, real-time web-based monitoring, and remote system management capabilities for non-conventional vessel applications.

Keywords: BNWAS; ESP3; Facial Landmark Detection; MediaPipe Face Mesh; VDR.

1. INTRODUCTION

In the era of the Industrial Revolution 4.0, the integration of Computer Vision (CV) and the Internet of Things (IoT) has significantly impacted the transportation sector to minimize human error (Dilek & Dener, 2023). Computer Vision technology has emerged as a key solution, enabling real-time physical condition analysis of operators to enhance operational safety standards (Seo et al., 2015). In the maritime context, safety is a paramount concern, yet fatigue among crew members remains a dominant factor in maritime accidents.

To mitigate these risks, international maritime regulations mandate the use of a Bridge Navigational Watch Alarm System (BNWAS) (Pamungkas et al., 2022). However, conventional BNWAS technologies are passive, relying on manual physical buttons, which creates security gaps as drowsy operators can press buttons reflexively without genuine awareness (Gokcek et al., 2022). Furthermore, non-conventional vessels often lack Voyage Data Recorders (VDR) due to high implementation costs (Abir et al., 2015). In addition to fatigue detection and voyage data recording, real-time monitoring interfaces are increasingly required to improve situational awareness and operational supervision in maritime safety

Naskah Masuk: 16 Mei 2026; Revisi: 25 Mei 2026; Diterima: 27 Juni 2026; Terbit: 08 Juli 2026

systems. Web-based monitoring platforms enable centralized visualization of operator conditions, alarm status, and operational monitoring data through lightweight embedded systems.

Previous studies on fatigue detection systems have primarily focused on standalone driver monitoring applications without integrating operational monitoring data recording, web based monitoring interfaces, and distributed embedded processing architectures (Dewi et al., 2022). In addition, existing BNWAS implementations generally rely on conventional operator acknowledgment mechanisms[4], while adaptive operational data logging capabilities are rarely integrated into low-cost maritime safety systems.

This study adopts the MediaPipe Face Mesh-based Facial Landmark algorithm to achieve high precision in monitoring facial states, particularly for detecting subtle signs of fatigue such as reduced eye-opening levels during microsleep. By mapping 468 3D facial coordinates, this approach provides a robust framework for real-time analysis of facial geometry (Sawant et al., 2025). Consequently, this research proposes the design of a Smart BNWAS integrated with VDR, which combines advanced facial landmark based fatigue detection processed on a Raspberry Pi 5 with voyage data logging powered by an ESP32-S3 microcontroller and web-based realtime monitoring capabilities.

Unlike conventional BNWAS implementations that primarily rely on manual operator interaction[4], the proposed system integrates real-time facial landmark-based fatigue detection with a low-cost ESP32-based Voyage Data Recorder (VDR) architecturen (Celecia et al., 2020). The proposed system combines Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR) analysis on a Raspberry Pi 5 with adaptive operational data logging, UART based distributed processing, real-time alert generation, and web based monitoring visualization.

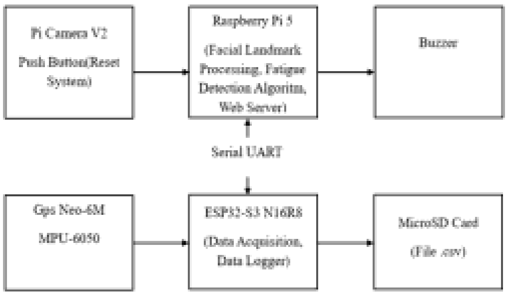
The proposed architecture is expected to provide a practical and cost-effective maritime safety solution for realtime operator monitoring, operational monitoring data recording, and web-based monitoring visualization on non-conventional vessels.

2. METHOD

This study employs an experimental approach to develop and evaluate the proposed Smart BNWAS-VDR system. The research methodology consists of system architecture design, facial landmark-based fatigue detection, decision-making algorithm development, data logging and communication implementation, and experimental system configuration.

System Architecture

The proposed system monitors operator alertness in real time by integrating vision-based fatigue detection with a low-cost Voyage Data Recorder (VDR) (Albadawi et al., 2023). It consists of three layers: data acquisition, processing and decision-making, and data logging with alert generation. A camera captures facial video, while GPS and RTC modules provide location and timestamp data. Video processing is performed on a Raspberry Pi 5 using MediaPipe Face Mesh to extract facial landmarks and calculate Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR) as fatigue indicators (Albadawi et al., 2023; Florez et al., 2024). The calculated values are evaluated to determine operator alertness. The Raspberry Pi also hosts a web-based dashboard for real-time monitoring of alertness status, EAR and MAR values, alarms, operational data, and video streaming. When fatigue is detected, status data are transmitted to the ESP32-S3 via UART, which records timestamps, GPS coordinates, MPU6050 measurements, and alertness status to a microSD card. This architecture separates processing, monitoring, and hardware control to support efficient real-time operation and reliable data logging, as shown in Fig. 1.



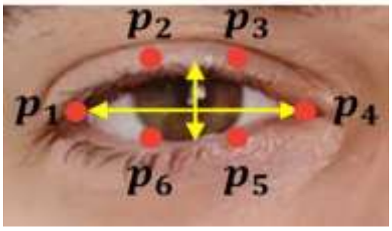
Picture 1. Block diagram of the proposed smart BNWAS-VDR system.

Facial Landmark Based Detection

The fatigue detection method is based on facial landmark analysis using the MediaPipe Face Mesh framework, which maps 468 three-dimensional facial landmarks to enable real-time monitoring of facial movements associated with fatigue (Sawant et al., 2025). The proposed approach focuses on the eye and mouth regions to calculate the Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR), which are widely used for detecting eye closure and yawning in fatigue monitoring systems (Sri Mounika et al., 2022). EAR is employed as the primary fatigue indicator and is calculated using:

$$EAR = \frac{\|p2 - p6\| + \|p3 - p5\|}{2\|p1 - p4\|} \tag{1}$$

p1 to p6 represent specific landmark points around the eye region. The vertical distances (p2–p6 and p3–p5) indicate eye opening, while the horizontal distance (p1–p4) represents eye width (Rupani et al., 2024).



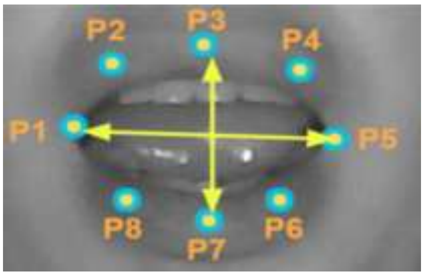
Picture 3. Eye landmark configuration used for EAR calculation

In addition, MAR is utilized as a complementary parameter to detect yawning behavior (Celecia et al., 2020) and is computed as:

$$MAR = \frac{\|p2 - p8\| + \|p3 - p7\| + \|p4 - p6\|}{2\|p1 - p5\|} \quad (2)$$

where p_1–p_8 represent mouth landmark points, with vertical distances indicating mouth opening and the horizontal distance indicating mouth width. A MAR threshold of **0.50** is applied to distinguish normal and yawning conditions, where values exceeding the threshold generate an early warning indication, while the final fatigue assessment remains primarily based on EAR (Kumar, 2025; Maheswari et al., 2022; Florez et al., 2024) The mouth landmark configuration used for MAR calculation is presented in **Fig. 3**.

Fig. 3 shows the configuration of mouth landmarks used in the MAR calculation.



Picture 4. Mouth landmark configuration used for MAR calculation.

By combining EAR and MAR, the proposed system improves the reliability of fatigue detection by simultaneously monitoring eye closure and yawning behavior (Li et al., 2020). These computed parameters are then processed by the decision-making algorithm to determine the operator's alertness state.

Decision Algorithm

The decision-making algorithm evaluates operator alertness in real time using Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR) derived from facial landmark analysis (Zhu et al., 2022). EAR functions as the primary fatigue indicator, where values below 0.25 for 3 consecutive seconds indicate fatigue to reduce false detection from normal blinking. MAR acts as a secondary indicator for yawning, with values above 0.50 triggering an early warning but not determining final fatigue status (Kumar, 2025; Maheswari et al., 2022; Florez et al., 2024). The Raspberry Pi then sends the system status to the ESP32 via UART to activate alarms and log timestamps, GPS coordinates, and status data to a microSD card. Logging occurs every 10 seconds under normal conditions and increases to 1-second intervals during warning or fatigue states until system reset.

Table 1. Threshold Parameters And System Responses

Parameter	Threshold	Duration	System Response
Ear	<0.25	3s	Alarm activation and 1-second logging
Mar	>0.50	N/A	Warning indication and 1-second logging

The overall decision-making and adaptive logging mechanism implemented in the proposed system is illustrated in Fig. 4.

Picture 5. Flowchart of the proposed decision-making algorithm.

Data Logging and Communication System

The proposed system utilizes **bidirectional UART communication** between the Raspberry Pi 5 and ESP32-S3 to support real-time monitoring and adaptive data logging (Khalid et al., 2024). The Raspberry Pi performs facial landmark processing and transmits operator alertness status to the ESP32-S3, while sensor data, including GPS, RTC, and MPU6050 measurements, are sent to the Raspberry Pi for web-based visualization. Operational data are stored in CSV format on a microSD card, and an adaptive logging mechanism records data every **10 s** during normal conditions and every **1 s** during warning or fatigue conditions to preserve critical events (Singh et al., 2020). In addition, the Raspberry Pi hosts a web-based dashboard that provides real-time alertness status, alarm information, voyage data, and live video streaming, enabling efficient monitoring and data management on the embedded platform.

Experimental Setup

The proposed Smart BNWAS-VDR system was implemented using a Raspberry Pi 5 for fatigue detection and web monitoring, and an ESP32-S3 for sensor integration and data logging. Hardware components included a Raspberry Pi Camera Module 2, MPU6050, GPS module, RTC module, and microSD card, while fatigue detection was developed in Python using OpenCV and MediaPipe with UART-based communication between devices (Bizdadea et al., 2025). Experiments were conducted in a controlled laboratory setting using a 640 × 480 pixel camera resolution and a 50–70 cm operator distance. System performance was evaluated through eye and mouth movement scenarios to validate EAR and MAR thresholds and verify subsystem integration before real maritime deployment. The hardware and software configuration is summarized in Table II.

Table 2. Experimental Setup And System Configuration

Component	Specification
Main processing unit	Raspberry Pi 5
Microcontroller	ESP32-S3
Camera module	Raspberry pi camera module 2
Facial landmark framework	Mediapipe facemesh
Image processing library	OpenCV
Programming language	Python
Firmware development environment	Arduino IDE
Communication protocol	UART serial communication
Camera resolution	640 x 480 pixels
Data storage	microSD card
Positioning module	GPS Module
Orientation sensor	MPU6050

3. RESULT AND DISCUSSION

This section presents the experimental results and performance evaluation of the proposed Smart BNWAS-VDR system. The discussion includes EAR and MAR detection performance, fatigue detection system behavior, UART communication and operational data logging performance, as well as web-based monitoring performance during continuous realtime operation.

Ear and Mar Detection Results

The performance of the proposed fatigue detection system was evaluated through real-time testing of Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR) under various operator conditions to validate the predefined decision-making thresholds. Experimental results showed that EAR values decreased significantly during eye closure (Dewi et al., 2022), (Rupani et al., 2024) and when the value remained below the threshold of 0.25 for 3 consecutive seconds, the system successfully classified the condition as fatigue and triggered an alarm response 25 (Rupani et al., 2024), (Fathima & Girisha, 2025), (Ma'ajid, 2025). In parallel, MAR was evaluated to identify yawning behavior as an early fatigue indicator, where the value increased noticeably during yawning conditions and generated a warning signal when exceeding the threshold of 0.50, indicating potential fatigue symptoms.

The combination of EAR and MAR parameters enables the proposed system to detect both eye-closure and yawning-related fatigue symptoms simultaneously (C. Chen et al., 2025). *Table 3. Ear Detection Results Ear detection results under normal and fatigue conditions, 5a. Left: Fatigue condition with EAR value below the threshold, 5b. Right: Normal condition with EAR value above the threshold.*

Table 3. Rata-rata Nilai Eye Aspect Ratio (EAR) pada Kondisi Mata Terbuka dan Tertutup (paling direkomendasikan)

Eye Condition	Samples	Average EAR
Open Eyes	10	0.2771
Closed Eyes	10	0.1763

The experimental results demonstrate that the proposed fatigue detection system effectively distinguishes operator conditions using Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR). Under normal conditions, the average EAR value was 0.2771, remaining above the predefined threshold of 0.25, whereas during eye closure the value decreased to 0.1763, representing a 36.4% reduction and enabling reliable identification of fatigue-related conditions. The clear separation between normal and fatigue thresholds minimizes ambiguity during real-time monitoring and supports previous findings that EAR decreases significantly during prolonged eye closure (Dewi et al., 2022; Rupani et al., 2024), In addition, MAR evaluation showed a significant increase during yawning conditions, and when values continuously exceeded the threshold of 0.50, the system successfully generated warning indications associated with early fatigue symptoms (Maheswari et al., 2022). These results confirm the effectiveness of EAR as the primary fatigue indicator and MAR as a supporting parameter within the proposed Smart BNWAS-VDR system.

MAR detection results under normal and yawning conditions, 6a. Left: Normal condition with MAR value below the threshold, 6b. Right: Yawning condition with MAR value above the threshold

Table 3. Mar Detection Results

Mouth Condition	Samples	Average MAR
Normal	10	0.2921
Yawning	10	0.7134

The experimental results show that MAR increased significantly during yawning conditions, confirming its effectiveness as an early fatigue indicator. The average MAR value increased from 0.2921 under normal conditions to 0.7134 during yawning, exceeding the predefined threshold of 0.50 and enabling clear differentiation between normal and fatigue-related mouth activity. When the threshold was continuously exceeded, the system generated a warning status transmitted to the ESP32-S3 for adaptive data logging and dashboard notification. These findings support previous studies and demonstrate that MAR is a reliable complementary parameter for early fatigue detection in the proposed Smart BNWAS-VDR system. The reliability of the EAR-based fatigue detection algorithm was further evaluated through accuracy testing, as presented in Table V.

Table 5. Hasil Evaluasi Akurasi Sistem Deteksi Berdasarkan Skenario Pengujian.

Detection Scenario	Total Test	Successful Detections	Incorrect Detections	Detection Success Rate
Open eyes	10	10	0	100%
Closed eyes	10	10	0	100%
Normal mouth	10	10	0	100%
Yawning	10	10	0	100%

The accuracy evaluation results indicate that the proposed fatigue detection system successfully classified all testing scenarios, achieving an accuracy of 100% under the experimental conditions. This performance can be attributed to the clear separation between the obtained EAR and MAR values and their respective thresholds. The average EAR values for normal and fatigue conditions remained consistently above and below the predefined threshold of 0.25(Rupani et al., 2024), (Fathima & Girisha, 2025), (Ma’ajid, 2025) while the average MAR values for normal and yawning conditions remained clearly separated from the threshold of 0.50. These findings demonstrate the effectiveness of the selected thresholds for reliable fatigue detection within the controlled testing environment.

Fatigue Detection System Performance

The proposed fatigue detection system was evaluated through real-time experiments under normal, eye-closure, and yawning conditions to assess decision-making and alarm performance. Results showed that the system successfully detected fatigue when the EAR value remained below the threshold of 0.25 for 3 seconds, triggering automatic alarm activation through ESP32-S3 via UART communication. The system also generated warning indications when the MAR value exceeded 0.50, identifying yawning as an early sign of fatigue (Albadawi et al., 2023). The reset function and adaptive logging mechanism operated as designed, recording data every 10 s under normal conditions and every 1 s during warning or fatigue events. Accuracy evaluation further showed 100% classification accuracy across all test scenarios, confirming that the selected EAR and MAR thresholds enabled reliable real-time fatigue monitoring, warning generation, and operational data logging in the proposed Smart BNWAS-VDR system.

Data Logging and Communication Results

The communication and data logging performance of the proposed Smart BNWAS-VDR system was evaluated through real-time operational testing. The experiments were conducted to verify the reliability of UART communication, operational data recording, timestamp synchronization, GPS acquisition, and orientation monitoring.

Experimental results show that the UART communication between the Raspberry Pi and ESP32-S3 operated successfully during system testing. The Raspberry Pi was able to transmit operator alertness status information, including normal, warning, and fatigue conditions, to the ESP32-S3 in real time without significant communication delay.

The data logging mechanism implemented on the ESP32-S3 also operated reliably throughout the experiments. Operational data were successfully stored in CSV format on the microSD card. Each recorded entry contained timestamp information obtained from the RTC module, GPS coordinates from the GPS module, roll and pitch orientation data acquired from the MPU6050 sensor, and the corresponding operator alertness status generated by the fatigue detection system.

Table 4. Example Of Operational Data Recorded In Csv Format

Timestamp	Latitude	Longitude	Roll	Pitch
2026-06-18 22:39:02	-7.922455	112.596817	0.49	-0.94
2026-06-18 22:39:04	-7.922461	112.596716	0.41	-0.12
2026-06-18 22:39:14	-7.922472	112.596771	-0.12	-0.88
2026-06-18 22:39:16	-7.922480	112.596774	-0.09	-1.77
2026-06-18 22:39:18	-7.922482	112.596763	-0.15	-0.49
2026-06-18 22:39:28	-7.922512	112.596725	-0.56	-0.71
2026-06-18 22:39:30	-7.922528	112.596694	0.46	-0.42
2026-06-18 22:39:32	-7.922538	112.596651	0.12	0.44
2026-06-18 22:39:44	-7.922543	112.596621	0.15	0.8
2026-06-18 22:39:46	-7.922543	112.596621	0.35	0.91

Table VI demonstrates the operational capability of the proposed ESP32-based VDR subsystem. The recorded CSV file contains synchronized timestamp information, GPS coordinates, and orientation parameters obtained from the MPU6050 sensor. The continuous sequence of recorded entries indicates that the UART communication and adaptive logging mechanisms operated reliably during system testing. These results confirm the capability of the proposed system to maintain structured operational data records for monitoring and post-event analysis purposes.

Further analysis of the recorded dataset shows that the logging process was performed continuously over an observation period of approximately 50 seconds, producing 26 consecutive records without missing entries or corrupted data fields. The recorded timestamps exhibit a consistent logging interval, indicating stable RTC operation and reliable data acquisition performance throughout the experiment. The complete availability of timestamp, positioning, and orientation information in each record demonstrates successful integration among the ESP32-S3, RTC module, GPS module, MPU6050 sensor, and microSD storage subsystem.

It should be noted that the first recorded entry contains latitude and longitude values equal to zero. This condition occurred because the GPS module had not yet acquired a valid satellite fix when the logging process was initiated. Consequently, valid positioning data were not available during the initial recording stage. After the GPS module successfully established satellite communication and obtained a valid position fix, latitude and longitude coordinates were continuously recorded in subsequent entries. This behavior is consistent with the normal initialization process of GPS receivers, which typically require an acquisition period before providing valid positioning information.

The recorded GPS coordinates changed gradually throughout the observation period without abnormal position jumps, indicating stable GPS signal acquisition and reliable real-time location tracking. The observed variations in latitude and longitude remained relatively small, corresponding to an estimated positional deviation of less than 5 m, which is within the expected accuracy range of the NEO-6M GPS receiver under normal operating conditions. Furthermore, the absence of sudden coordinate fluctuations suggests that the GPS subsystem maintained stable satellite reception during the experiment.

Analysis of the orientation data shows that the roll angle ranged from −3.67° to 4.16°, while the pitch angle ranged from −0.78° to 0.71°. These values indicate that the monitored platform remained in a relatively stable condition throughout the testing period, while the MPU6050 sensor continuously captured small orientation changes. The successful recording of roll and pitch parameters confirms the capability of the proposed VDR subsystem to acquire and store vessel attitude information together with positioning and timestamp data. Overall, the results validate the reliability of the proposed ESP32-S3-based VDR subsystem for continuous voyage data recording, operational monitoring, and post-event data analysis applications.

Table 5. Data Logging and Communication Results

Component	Function	Result
Uart Communication	Real Time Status Transmission	Operational data was succesfully transmitted from ESP32-S3 to Raspberry Pi 5 during all test scenarios
microSD card	CSV Data Logging	Fatigue events, GPS coordinates, roll-pitch orientation data and timestamp information were successfully recorded in CSV format.
GPS Module	Location Recording	GPS coordinates were successfully displayed and stored during monitoring
MPU-6050	Roll-Pitch Monitoring	Roll and pitch values were succesfully acquired and visualized on the monitoring dashboard

Web Based Monitoring Performance

The proposed system also implements a web-based monitoring interface hosted on the Raspberry Pi 5 to visualize operator alertness status and operational monitoring data in real time. The monitoring dashboard was evaluated during continuous system operation to verify realtime status updates, alarm visualization, sensor monitoring, and overall system accessibility through a browser-based platform connected over a local network.

Experimental results show that the web-based monitoring interface successfully displayed operator conditions, including normal, warning, and fatigue states, during realtime system operation. The dashboard continuously updated operator alertness status without interrupting the facial landmark processing and fatigue detection tasks running on the Raspberry Pi 5. Alarm conditions generated during warning and fatigue events were also displayed successfully on the monitoring interface in real time.

In addition to operator alertness monitoring, the dashboard successfully visualized operational monitoring data, including timestamp information obtained from the RTC module, GPS coordinates and roll and pitch orientation data from the MPU6050 sensor. The web interface also displayed adaptive logging status information during normal, warning, and fatigue conditions.

The implemented web-based monitoring system successfully supports real-time video streaming while simultaneously performing fatigue detection, alarm monitoring, and voyage data visualization. This approach reduced computational overhead on the Raspberry Pi 5 while maintaining stable facial landmark processing, UART communication, and operational data logging performance during continuous system operation.

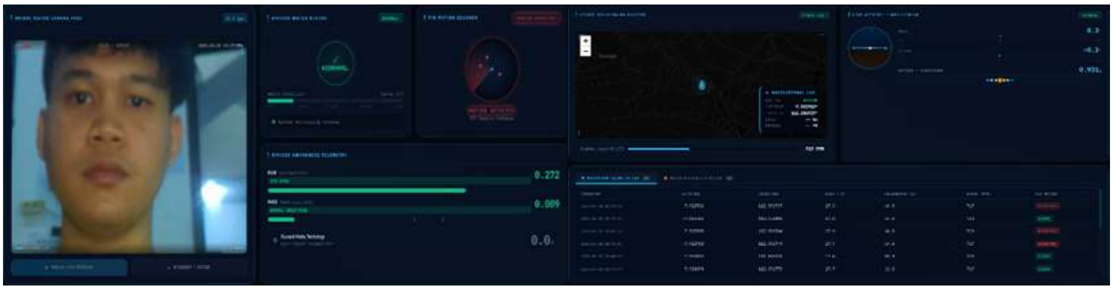
The monitoring dashboard could be accessed successfully through devices connected to the same local network using a standard web browser. During experimental testing, the web-based monitoring interface operated continuously without causing significant delay in system response, alarm activation, or adaptive operational data logging processes.

The web-based monitoring dashboard also supports remote shutdown functionality. During testing, authorized users successfully initiated Raspberry Pi shutdown operations through the web interface. The shutdown command was correctly processed by the operating system, demonstrating the feasibility of integrating monitoring and system management functions within a single platform.

The remote shutdown feature enables safe system maintenance and power management without requiring direct physical access to the Raspberry Pi 5, which may be beneficial when the monitoring unit is installed in confined or difficult-to-access locations.Overall, the experimental results demonstrate that the proposed web-based monitoring system operated reliably and effectively for realtime visualization of operator conditions, alarm status, and operational monitoring data for maritime safety applications.

2. Web based monitoring dashboard, 7a. Left: operator monitoring and fatigue detection 7b. Right: navigation and operational data monitoring

e-ISSN: 2963-7805; p-ISSN: 2963-8208, Hal. 199-215



Web based monitoring dashboard, 7a. Left: operator monitoring and fatigue detection 7b. Right: navigation and operational data monitoring

Fig. 7 shows the web-based monitoring dashboard implemented on the proposed Smart BNWAS-VDR system. The dashboard displays operator alertness status, alarm conditions, GPS information, roll and pitch orientation, and camera visualization during realtime monitoring operation.

Tabel 3. Hasil Pengujian Fungsi dan Kinerja Sistem Monitoring

Parameter	Result
Live video streaming	Real-time camera streaming was succesfully displayed on the web dashboard
Alarm status visualization	Fatigue warning and alarm status were succesfully displayed in real time
GPS monitoring visualization	Real-time GPS coordinates were successfully visualized and updated.
Roll and pitch monitoring	Roll and pitch information were succesfully displayed in real time
Stable realtime monitoring operation	The monitoring dashboard operated continously during testing
Raspberry Pi Shutdown Control	Successfully executed through web dashboard

Raspberry Pi 5 Web Based Monitoring Results

Table VIII summarizes the performance results of the proposed web-based monitoring interface during realtime system operation. Experimental results indicate that the dashboard successfully visualized operator conditions, alarm status, operational monitoring data, and system monitoring information without interrupting realtime fatigue detection performance on the Raspberry Pi 5.

System Discussion

Based fatigue detection, operational data logging, and web-based monitoring into a unified low-cost maritime safety platform. The combination of eye aspect ratio (ear) and mouth aspect ratio (mar) analysis enabled reliable identification of fatigue-related symptoms, including prolonged eye closure and yawning behavior, under the controlled testing conditions (zhu et al., 2022). The clear separation between the measured ear and mar values and their respective thresholds contributed to the stable performance of the decision-making algorithm and supported accurate fatigue classification during real-time operation.

The distributed processing architecture implemented in the proposed system also contributed significantly to overall system performance. Computationally intensive facial landmark detection and web-based monitoring tasks were executed on the raspberry pi 5, while the esp32-s3 was dedicated to sensor acquisition, uart communication, and adaptive data logging. This separation of responsibilities reduced processing overhead on the embedded subsystem and enabled simultaneous fatigue monitoring, alarm generation, and operational data recording without noticeable degradation in system responsiveness.

Another important contribution of this work is the integration of a low-cost voyage data recorder (vdr) subsystem into the smart bnwas architecture. Unlike conventional vdr implementations that rely on dedicated recording hardware and compliance with maritime recording standards (hopcraft et al., 2023), the proposed system utilizes an esp32-s3, gps module, rtc module, mpu6050 sensor, and microsd storage to provide structured operational data recording. The use of low-cost embedded hardware is also consistent with recent efforts to develop cost-effective maritime monitoring solutions for small-scale and non-conventional vessels. The proposed subsystem is intended as a simplified low-cost vdr implementation and does not aim to fully replace standard imo-compliant voyage data recorder systems.

Unlike conventional fatigue detection systems, the proposed platform not only detects operator fatigue but also records operational voyage data including timestamps, positioning information, and vessel orientation parameters for future analysis and incident investigation purposes. This integration enables the proposed platform to function not only as a fatigue monitoring system but also as a simplified voyage data recorder for maritime safety applications.

The implementation of a web-based monitoring dashboard further enhances system usability by providing real-time visualization of operator alertness status, alarm conditions, gps information, orientation data, and live camera streaming through a standard web browser (c.-y. Chen et al., 2024).the experimental results indicate that the monitoring interface operated continuously without interrupting fatigue detection and data logging processes, demonstrating the feasibility of integrating real-time monitoring and operational data management within a single embedded platform.

The reported 100% accuracy was obtained under controlled laboratory conditions using a limited number of testing scenarios. Therefore, the results should be interpreted as an initial validation of system functionality rather than a comprehensive assessment of real-world operational performance.

Despite the promising results, several limitations should be acknowledged. All experiments were conducted under controlled laboratory conditions rather than onboard an actual vessel. Consequently, environmental factors such as vessel motion, vibration, changing illumination, weather conditions, and varying operator positions were not evaluated in this study. In addition, the fatigue detection evaluation was performed using a limited number of testing scenarios and samples, which may not fully represent the diversity of real-world operational conditions. Therefore, further validation under operational maritime environments is required before large-scale deployment.

Future work will focus on conducting onboard evaluations in real maritime environments, expanding the number of test subjects and operational scenarios, and investigating adaptive thresholding or machine learning approaches to improve fatigue detection robustness under varying environmental conditions (hu et al., 2024). Additional integration with maritime communication systems and cloud-based monitoring platforms may also enhance the practical applicability of the proposed smart bnwas-vdr system for maritime safety operations (abbas & alsheddy, 2020).

4. KESIMPULAN DAN SARAN

This study proposed and implemented a Smart Bridge Navigational Watch Alarm System integrated with a low-cost Voyage Data Recorder (Smart BNWAS-VDR) based on Raspberry Pi 5 and ESP32-S3 architecture. The system integrates facial landmark-based fatigue detection, real-time web monitoring, UART communication, and operational data logging into a unified platform, where fatigue is identified using Eye Aspect Ratio (EAR) and Mouth Aspect Ratio (MAR) extracted through MediaPipe Face Mesh to detect prolonged eye closure and yawning behavior. Experimental results under controlled laboratory conditions demonstrated that the system effectively detected fatigue conditions, generated warning and alarm responses, recorded operational data in CSV format, and enabled real-time monitoring and remote shutdown through a web-based dashboard. The ESP32-S3-based VDR subsystem also successfully recorded timestamps, GPS coordinates, and orientation data, while adaptive logging improved storage efficiency by increasing recording frequency during warning and fatigue events. Overall, the proposed system demonstrates the feasibility of integrating fatigue monitoring and voyage-data recording into a low-cost embedded platform for non-conventional vessel applications, with future work focusing on real maritime validation and the development of adaptive thresholding and machine-learning-based approaches to enhance detection robustness.

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