
Wireless AI-Based Biomedical Parameter Monitoring System for Human Health and Fatigue Detection

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Abstract.

Continuous monitoring of physiological parameters is essential for improving healthcare outcomes and ensuring occupational safety in high-risk environments. Traditional monitoring methods rely on periodic clinical assessments, which are insufficient for detecting real-time physiological changes. This paper presents a wireless AI-based biomedical monitoring system that integrates wearable sensors, embedded processing, and intelligent analytics to enable real-time health monitoring and fatigue detection. The system collects physiological data such as heart rate, oxygen saturation, temperature, and stress indicators using wearable devices. These signals are processed through an embedded controller and analysed using lightweight machine learning techniques. A vision-based module enhances fatigue detection by identifying behavioural indicators such as eye closure and yawning. The processed data is transmitted to a cloud-based dashboard, enabling remote monitoring and alert generation. The results indicate that the proposed system achieves improved accuracy, reduced latency, and efficient real-time performance, making it suitable for industrial safety and remote healthcare applications.

Keywords. Biomedical Monitoring, Internet of Things (IoT), Wearable Sensors, Edge AI, Fatigue Detection, ESP32, Wireless Communication.

1. INTRODUCTION

Industrial environments require continuous attention, physical effort, and quick decision-making. Fatigue and physiological imbalance significantly affect human performance and increase the likelihood of accidents. Traditional monitoring approaches rely on periodic medical evaluation, which fails to capture real-time physiological variations. Wearable sensor technology has enabled continuous monitoring of vital parameters such as heart rate and stress levels. When combined with Artificial Intelligence (AI), these systems can identify abnormal patterns and provide early warnings.

Edge computing further enhances system performance by processing data locally, reducing latency and preserving privacy [1]. Physiological indicators such as heart rate variability (HRV) and galvanic skin response (GSR) have been widely used for fatigue detection [3]. Integrating these signals with behavioral indicators such as eye closure improves detection accuracy.

This paper proposes a hybrid system combining wearable sensing, computer vision, and AI-based processing to enable real-time fatigue detection and health monitoring.

2. LITERATURE SURVEY

Modern wearable devices enable continuous monitoring of physiological signals, allowing early detection of abnormal health conditions and improving diagnostic efficiency [1].

These systems typically consist of sensing, processing, and communication layers that support real-time health tracking. Energy-efficient embedded systems are essential for wearable applications. Lee and Al Faruque demonstrated optimized processing techniques for low-power biomedical devices [2].

Machine learning models further enhance system intelligence by analyzing complex physiological data patterns [3].

Edge AI has gained attention for real-time applications, allowing models to run directly on embedded systems [4]. Vision-based fatigue detection using facial features has also shown promising results [7]. Despite advancements, challenges such as data privacy, sensor accuracy, and energy efficiency remain critical.

3. KEY CONTRIBUTION

This paper makes the following key contributions to the field of AI-based healthcare monitoring and fatigue detection:

1. **Integrated Multimodal Monitoring Framework:** A unified system is developed that combines physiological sensing (HR, SpO₂, temperature, GSR) with vision-based fatigue detection, enabling more accurate and reliable assessment of human health conditions compared to single-modality systems.
2. **Edge AI-Enabled Real-Time Processing:** The proposed system deploys lightweight machine learning models on an embedded platform (ESP32), enabling real-time decision-making with reduced latency and improved data privacy, minimizing reliance on cloud infrastructure.
3. **Hybrid Architecture for Scalable Monitoring:** A layered architecture integrating edge computing and cloud analytics is designed to support both real-time local processing and long-term data analysis, ensuring scalability and efficient resource utilization.
4. **Multi-Level Intelligent Alert Mechanism:** The system introduces a hierarchical alert system (local alerts, mobile notifications, and dashboard warnings) for early detection of fatigue and stress, improving safety in industrial and healthcare environments.
5. **Efficient Data Processing Pipeline:** A complete workflow including data acquisition, pre-processing, feature extraction, and classification is implemented to ensure reliable analysis of both physiological and behavioural signals.
6. **Low-Cost and Practical Implementation** the use of affordable sensors and embedded hardware makes the system cost-effective and suitable for real-world deployment, especially in resource-constrained environments.

4. SYSTEM ARCHITECTURE

The system follows a layered architecture consisting of:

- **Sensor Layer:** Collects physiological data (HR, SpO₂, temperature, GSR)
- **Edge Layer:** ESP32 performs pre-processing and feature extraction
- **AI Layer:** Machine learning model classifies user state
- **Communication Layer:** Wi-Fi transmits data
- **Cloud Layer:** Stores and analyses data
- **Application Layer:** Dashboard displays results



Fig 4.1. System Architecture of the proposed AI-based biomedical monitoring system.

5. METHODOLOGY

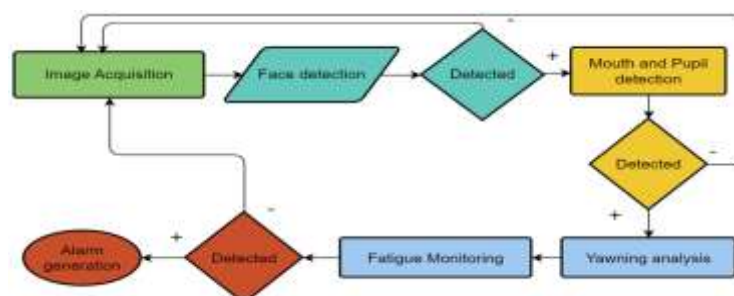


Fig 5.2. Methodology workflow for fatigue detection and health monitoring.

The system operates through the following steps:

1. Data Acquisition: Sensors collect physiological signals and camera captures facial data
2. Pre-processing: Noise removal and normalization
3. Feature Extraction: HRV, stress level, blink rate, yawning frequency
4. AI Classification: Model classifies user condition
5. Communication: Data transmitted using Wi-Fi/MQTT
6. Visualization: Dashboard displays real-time results
7. Alert Generation: Alerts triggered based on fatigue level

6. PROPOSED SYSTEM

- MAX30102 Sensor: Measures heart rate and oxygen saturation (SpO₂), providing key indicators of cardiovascular health.
- GSR Sensor: Monitors skin conductance to estimate stress and emotional response levels.
- Temperature Sensor: Tracks body temperature variations, helping detect abnormal physical conditions.
- ESP32 Controller: Acts as the main processing unit, handling data acquisition, pre-processing, and execution of the AI model.
- Camera Module: Captures facial images to analyse fatigue-related features such as eye closure and yawning.
- Edge AI Model: Performs real-time classification of user conditions (normal, fatigued, stressed) directly on the device.
- Cloud Database: Stores collected data and supports remote monitoring and long-term analysis.
- Dashboard Interface: Displays real-time health parameters, fatigue levels, and alerts for users and supervisors.

7. RESULTS AND PERFORMANCE ANALYSIS

The system was evaluated using collected physiological and visual data under controlled conditions.

Table 1 Experimental results

Parameter	Value
Accuracy	95.2%
Precision	92.8%
Recall	94.1%
F1 Score	93.4%
Response Time	1.3 sec

The results show that the system achieves high accuracy in identifying fatigue conditions, demonstrating reliable classification of physiological and behavioural states. The integration of multiple data sources improved performance compared to single-modality systems. The response time confirms the efficiency of edge processing.

8. DISCUSSION

The experimental results indicate that the proposed system effectively detects fatigue and monitors physiological conditions in real time. The use of both physiological signals and vision-based features improves detection accuracy compared to single-modality approaches [3].

Edge-based processing on the ESP32 reduces latency and enables quick response, making the system suitable for real-time applications [1]. The wireless communication module also demonstrates reliable data transmission with minimal delay, supporting continuous monitoring through the cloud platform [7].

However, minor limitations were observed due to sensor noise and variations in lighting conditions affecting the vision module. Despite these challenges, the system provides a balanced performance in terms of accuracy, speed, and efficiency.

9. CONCLUSION

The proposed AI-based biomedical monitoring system provides an efficient solution for real-time health monitoring and fatigue detection. By integrating wearable sensors, edge computing, and AI analytics, the system enables proactive healthcare management and improved occupational safety.

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