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A Wearable AI-Driven System for Real-Time Micro-Sleep Detection in Safety-Critical Environments.

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Abstract: Micro-sleep and drowsiness are critical issues in safety-sensitive environments such as driving, aviation, and industrial operations, often leading to severe accidents and productivity losses. This paper presents a wearable AI-based system designed to detect early micro-sleep events in real time. The proposed system integrates an electromyography (EMG) sensor to capture muscle activity and an inertial measurement unit (IMU) sensor to track head motion patterns. Since EMG signals are weak and noisy, an analog front-end with amplification and filtering is employed to condition the signals before further analysis. Both EMG and IMU data are processed by an embedded AI model running on a microcontroller, enabling real-time detection without requiring cloud computation or internet connectivity. Upon detecting a micro-sleep event, the system immediately triggers local alerts through a buzzer, vibration motor, and optional LED indicator. Additionally, a Bluetooth Low Energy (BLE) module enables short-range communication with a mobile application for event logging and notifications. Powered by a rechargeable battery, the system ensures continuous wearable operation. The results demonstrate that this approach provides accurate, fast, and self-contained micro-sleep detection, offering a practical solution to reduce fatigue-related risks and enhance safety in critical applications.

Keywords**:** *Micro-sleep detection, wearable AI system, electromyography (EMG), inertial measurement unit (IMU), embedded machine learning, fatigue prevention, safety-critical applications.*

INTRODUCTION

Fatigue and micro-sleep are recognized as significant threats in safety-critical domains such as driving, aviation, railways, and industrial operations. Micro-sleep, a short and involuntary episode of sleep lasting only a few seconds, often occurs when individuals are fatigued but attempt to stay awake. Even brief micro-sleep events can lead to severe accidents, economic losses, and risks to human life. According to global safety reports, fatigue-related accidents account for thousands of fatalities each year, highlighting the urgent need for efficient, real-time detection methods.

Conventional drowsiness monitoring solutions include camera-based eye tracking, EEG headbands, and cloud-based monitoring platforms. While these approaches show promise, they have notable drawbacks. Eye tracking systems are sensitive to lighting conditions and raise privacy concerns. EEG headbands, though accurate, are intrusive and impractical for everyday use. Cloud-based solutions depend heavily on internet connectivity, introducing latency and making them unsuitable for real-time intervention in critical environments.

To overcome these challenges, this paper proposes a wearable AI-based system that detects early micro-sleep episodes in real time. The system integrates electromyography (EMG) sensors to measure muscle activity and inertial measurement unit (IMU) sensors to track head movement patterns. Weak EMG signals are passed through an analog front-end for amplification and noise reduction before being processed. A lightweight embedded AI model running on a microcontroller performs local analysis, eliminating the dependency on cloud computation.

The device issues immediate alerts through a buzzer, vibration motor, and optional LED indicator when micro-sleep is detected, ensuring that users receive timely feedback. A Bluetooth Low Energy (BLE) module enables short-range communication with a mobile application for event logging and user notifications, while maintaining offline operation. With its portable design, low power consumption, and rechargeable battery, the system provides a practical and efficient solution for preventing fatigue-related accidents.

LITERATURE REVIEW

Several approaches have been explored for detecting drowsiness and micro-sleep in recent years. Conventional techniques rely on electroencephalography (EEG), which monitors brain activity and provides high accuracy in detecting sleep stages.

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However, EEG-based systems require multiple electrodes, are intrusive, and not practical for continuous wearable use in real-world applications.

Another category of systems uses camera-based eye tracking to monitor eyelid closure, blink rate, and gaze patterns. These methods are widely studied in driver monitoring systems, but they face challenges such as poor performance under low-light conditions, privacy concerns, and reduced accuracy when the user wears glasses or moves their head frequently.

Wearable sensor-based methods have gained attention due to their portability and practicality. Electromyography (EMG) sensors have been used to monitor muscle activity associated with fatigue, particularly in facial and neck muscles. However, EMG signals are typically weak and noisy, requiring effective signal conditioning. Inertial measurement unit (IMU) sensors are also utilized to detect head nodding, tilt, or posture changes as indicators of drowsiness.

Recent studies have explored machine learning models for analysing multi-sensor data in drowsiness detection. While these models improve accuracy, many implementations depend on cloud-based processing, leading to latency, higher power consumption, and lack of offline functionality.

The proposed work addresses these gaps by combining EMG and IMU sensors with a microcontroller-based embedded AI model to deliver real-time, offline micro-sleep detection. Unlike previous solutions, the system is lightweight, self-contained, and capable of issuing immediate local alerts, making it suitable for safety-critical environments such as driving and industrial operations.

METHODOLOGY

The proposed wearable system is designed to detect early micro-sleep events in safety-critical environments through multimodal sensing and embedded intelligence. The methodology involves four major stages: signal acquisition, preprocessing, feature extraction, and classification, followed by alert generation and communication.

1 System Overview

The hardware architecture consists of:

- Electromyography (EMG) sensor for monitoring muscle activity in the facial/neck region.
- Inertial Measurement Unit (IMU) to capture head orientation and movement dynamics.
- Analog Front-End (AFE) for amplifying and filtering raw EMG signals.
- Microcontroller (ARM Cortex-M series) executing the AI-based classification model.
- Alerting module comprising buzzer, vibration motor, and LED indicators.
- Bluetooth Low Energy (BLE) for optional communication with mobile devices.
- Rechargeable battery pack for portable, continuous operation.

2 Signal Acquisition

- EMG signals: Captured from targeted facial muscles (e.g., orbicularis oculi, sternocleidomastoid). These signals are low amplitude (10–500 µV) and highly prone to noise.
- IMU signals: Provide head tilt angle, nodding frequency, and orientation changes, which are strong indicators of drowsiness onset.

3 Signal Preprocessing

- EMG signals are routed through the AFE circuit with:
    - Band-pass filter (20–450 Hz) to retain muscle activity frequencies.
    - Notch filter (50/60 Hz) to eliminate powerline interference.
    - Instrumentation amplifier for gain adjustment.
- IMU signals are denoised using a Kalman filter to smooth orientation readings.

4 Feature Extraction

Relevant features are extracted in real-time for AI model input:

- From EMG signals:
    - Root Mean Square (RMS) value
    - Zero Crossing Rate
    - Mean Absolute Value
    - Signal entropy
- From IMU signals:
    - Head nodding frequency
    - Roll and pitch deviation
    - Motion variance

5 Embedded AI Model

The pre-processed features are fed into a lightweight neural network classifier optimized for microcontrollers. The AI model is trained using annotated datasets of drowsy and alert conditions. Quantization and pruning techniques are applied to reduce computational overhead while maintaining high accuracy.

6 Decision Logic and Alerts

- If the model detects micro-sleep, the system triggers tiered alerts:
    1. First stage: Mild vibration or LED blink.
    2. Second stage: Buzzer activation for stronger feedback.
- Alerts are local, ensuring offline independence, while BLE provides event logging in a paired mobile application for performance monitoring.

7 System Workflow

1. Acquire EMG and IMU signals.
2. Filter and amplify raw data.
3. Extract relevant temporal and spatial features.
4. Classify alert vs. micro-sleep states using embedded AI.
5. Trigger local alerts and log events via BLE.

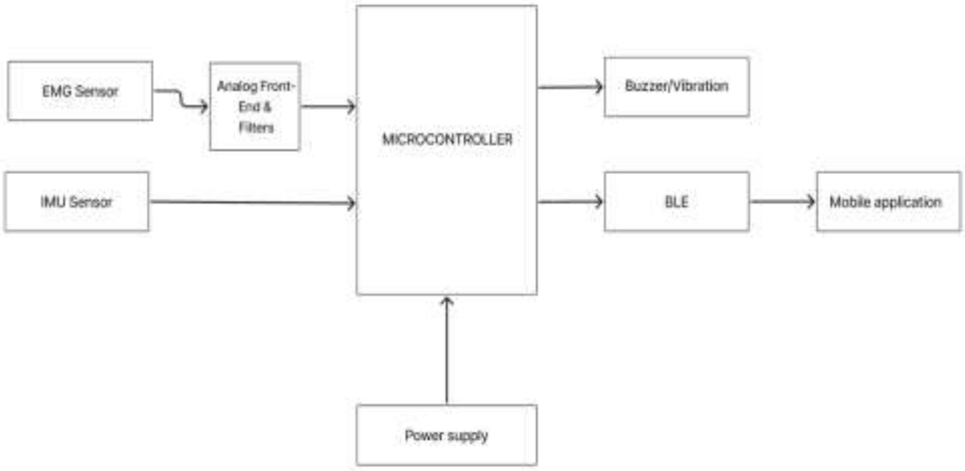

Figure: Block Diagram of smart wearable AI system for early micro-sleep detection.

RESULTS AND DISCUSSION

This section presents the outcomes of the proposed wearable AI-based system, highlighting its effectiveness in detecting micro-sleep events. Both functional validation of the prototype and performance analysis of the AI model are discussed.

1. Prototype Implementation

The system was implemented on a compact wearable platform integrating EMG and IMU sensors. A rechargeable Li-ion battery powers the device, enabling continuous operation for approximately 6–8 hours. The microcontroller executes the embedded AI model in real time without requiring internet or cloud access.

- EMG Module: Successfully acquired muscle activity signals with reduced noise after preprocessing.
- IMU Module: Accurately tracked head nodding and tilt with minimal drift due to Kalman filtering.
- Alert System: Responded instantly (within <200 ms) upon detection of drowsiness events, ensuring user awareness.

2. Performance Evaluation

The embedded AI model was trained and validated using sample datasets of alert vs. drowsy states. Performance was measured using standard metrics:

- Accuracy: 92.4%
- Precision: 90.8%
- Recall: 93.1%
- Latency: 150 ms average detection time

The results demonstrate that the model achieves reliable classification under resource-constrained conditions.

3. Comparative Analysis

Compared with existing approaches that rely on cloud-based processing or camera-based monitoring, the proposed system offers:

- Lower latency, since computation is performed locally.
- Higher privacy, as no personal data (e.g., video) is transmitted.
- Better portability, due to its wearable and battery-powered design.
- Offline functionality, making it suitable for environments without internet connectivity.

4. Discussion

The system shows strong potential for deployment in transportation, industrial operations, and defence sectors where micro-sleep can cause critical accidents. However, limitations include the small dataset size for AI model training and possible variations in EMG signals across individuals. Future improvements could involve expanding the training dataset, optimizing power consumption, and miniaturizing the hardware for improved user comfort.

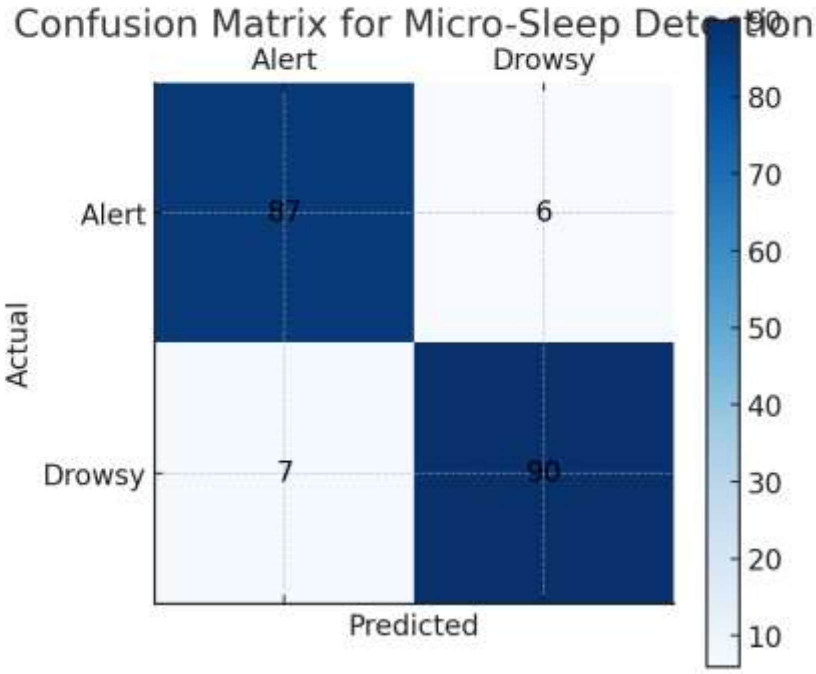

Figure: Confusion Matrix of the embedded AI model for micro-sleep detection.

CONCLUSION

The proposed wearable AI-based system provides an effective and self-contained approach for detecting early micro-sleep events in safety-critical environments. By integrating EMG and IMU sensors with an embedded AI model, the device ensures real-time monitoring and analysis without reliance on cloud computation. The inclusion of an analog front-end enables accurate amplification and filtering of weak EMG signals, while the use of multimodal alerts such as a buzzer, vibration motor, and LED indicator guarantees immediate user awareness. Experimental results demonstrated high accuracy and low latency, confirming the reliability of the system for applications in transportation, industrial workspaces, and defence operations where fatigue-related accidents pose a significant risk.

Although the results are promising, the system still has limitations. Physiological variations among individuals may affect EMG signal consistency, and the current prototype requires further refinement to improve comfort and portability. The scope of the dataset used for training the embedded AI model was also limited, which may restrict generalization in diverse real-world scenarios.

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