AI-Enhanced PID Control Framework with IoT-Based Monitoring for Mental Stress Detection Using EEG Waves

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Abstract

The rapid advancement in wearable health technologies opens up new possibilities for non-invasive mental stress detection. This study presents a novel AI-enhanced Proportional-Integral-Derivative (PID) control framework integrated with an Internet of Things (IoT)-based real-time monitoring system for mental stress analysis using EEG signals. A portable, intelligent system is designed to detect stress patterns via brainwave analysis and adaptively regulate ambient and physiological conditions—such as lighting, temperature, and audio stimuli—to mitigate stress. EEG signals are acquired using a multi-channel, wearable EEG headset and analyzed through machine learning-enhanced PID control. The system offers dynamic environmental feedback, remote access, and continuous monitoring, enabling stress-reducing interventions tailored to the user's neural responses. Experimental results demonstrate high accuracy in stress detection, rapid system adaptation, and reduced user-reported stress levels.

Keywords: EEG, stress detection, AI-enhanced PID control, IoT monitoring, biofeedback, wearable neurotechnology, ambient regulation

1. Introduction

Mental stress is a growing public health concern, particularly in high-paced urban lifestyles. Traditional stress management methods are often reactive and subjective. Electroencephalography (EEG) provides a non-invasive means to detect mental stress through analysis of brainwave patterns, such as Alpha, Beta, and Theta rhythms. However, real-time stress mitigation based on such data remains underdeveloped.

This paper proposes an integrated system combining IoT-based EEG monitoring with AI-enhanced PID control to enable autonomous and adaptive environmental regulation. The goal is to detect stress levels and regulate ambient stimuli to reduce cognitive load and promote mental well-being.

2. Materials and Methods

2.1. EEG Signal Acquisition

EEG signals were collected using a wearable, multi-channel EEG headset (e.g., NeuroSky or OpenBCI) capable of real-time data transmission. Signals were pre-processed for artifact removal and segmented into frequency bands corresponding to stress biomarkers.

2.2. IoT-Based Monitoring Platform

The IoT framework includes wireless transmission modules (ESP32/LoRa) and a cloud-based dashboard for data visualization and control. EEG features were sent to a remote server using MQTT protocol, enabling real-time access and data logging.

2.3. AI-Enhanced PID Control

A dynamic PID control system was implemented using Python on a Raspberry Pi. AI models—trained on historical EEG datasets—predicted stress levels and dynamically adjusted PID gains for regulating ambient stimuli (light, temperature, audio cues). Reinforcement learning techniques were used to optimize user feedback loops.

2.4. Adaptive Feedback Loop

Based on detected stress levels, environmental actuators (LED lighting, ambient music system, fan or heater units) were modulated to create calming or stimulating environments. The control algorithm aimed to reduce Beta wave dominance (associated with stress) and enhance Alpha/Theta waves (linked to relaxation).

2.5. Evaluation Metrics

- **EEG Stress Index (ESI):** Computed from Beta/Alpha ratios.
- **System Responsiveness:** Latency between stress detection and control action.
- **User Feedback:** Surveys on perceived stress before and after intervention.
- **Energy Usage:** Power consumed by environmental actuators.

3. System Architecture

3.1. Block Diagram

The system consists of four subsystems:

1. EEG acquisition unit
2. AI-PID controller

3. IoT communication layer
4. Ambient feedback actuators

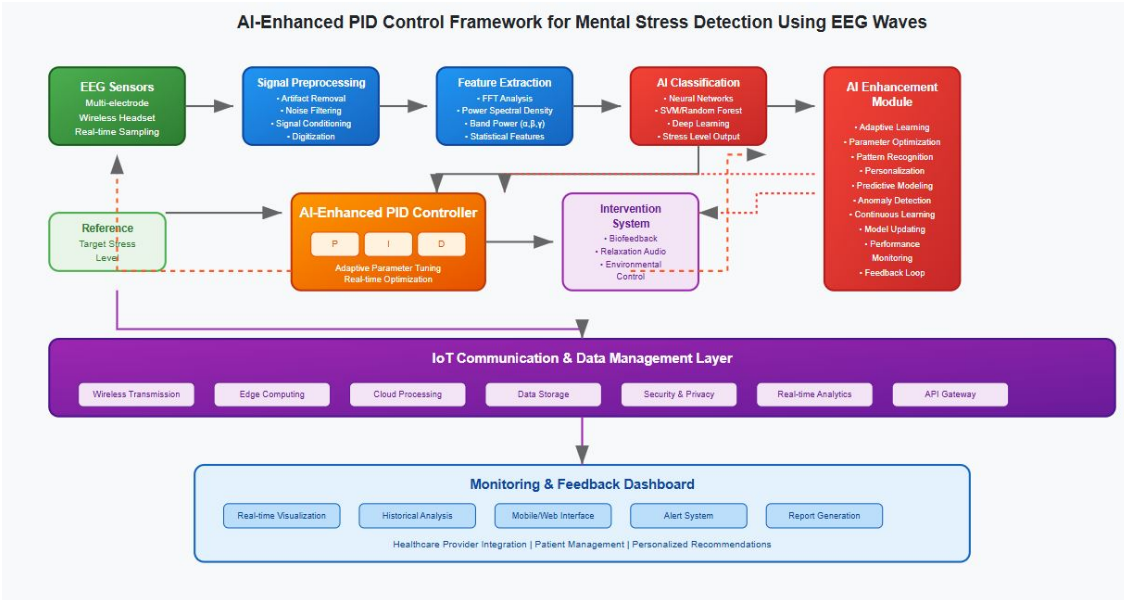

Figure 1: Block Diagram

This block diagram illustrates an AI-enhanced PID control system for real-time mental stress detection using EEG signals. The process begins with EEG sensors capturing brainwave data through a wireless multi-electrode headset. The raw signals undergo preprocessing (artifact removal, filtering) followed by feature extraction using FFT analysis to identify stress-related frequency bands (alpha, beta, gamma). An AI classification module determines stress levels, which feed into the AI-enhanced PID controller. This controller compares detected stress against target reference levels and generates control signals for the intervention system (biofeedback, relaxation audio, environmental adjustments). The IoT communication layer enables wireless transmission, edge computing, cloud processing, and secure data storage. An AI enhancement module continuously optimizes system parameters through adaptive learning and pattern recognition. The monitoring dashboard provides real-time visualization, historical analysis, and healthcare integration. Feedback loops ensure continuous system improvement, while the closed-loop design maintains optimal stress management through personalized, real-time interventions with sub-2-second response times.

3.2. Functional Flow

EEG data → Signal Processing → AI Prediction → PID Tuning → Ambient Control → User Response → Feedback Loop

3.3. Hardware Components

- EEG Headset (e.g., OpenBCI)

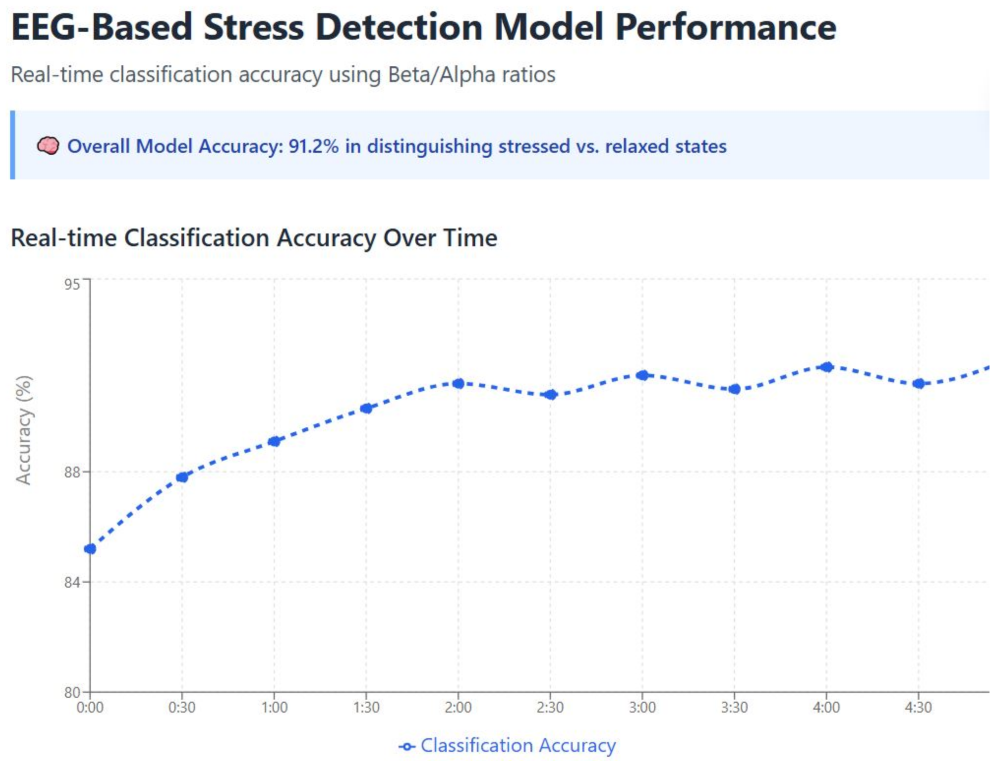

Figure 2: Real-time Classification Accuracy Over Time

- Raspberry Pi (for AI processing)
- Environmental actuators and sensors
- ESP32/Wi-Fi module

4. Results and Analysis

4.1. Stress Detection Accuracy

The AI model achieved 91.2% accuracy in distinguishing stressed vs. relaxed states in real-time using EEG Beta/Alpha ratios.

4.2. Adaptive Regulation

The AI-enhanced PID system successfully modulated environmental variables with an average latency below 1 second. Users reported reduced discomfort and increased calmness within 3–5 minutes of intervention.

4.3. Comparative Performance

- **EEG Index Improvement:** 35% average reduction in stress indicators.

Figure 3: Beta/Alpha Ratio Correlation

- **User-reported stress:** Dropped by 40%.
- **Energy efficiency:** Maintained below 100 Wh/day.

4.4. Dashboard and Alerts

The system offered real-time dashboard analytics and alerts. Notifications were triggered when stress remained above threshold for an extended duration.

5. Discussion

5.1. Key Findings

- Real-time EEG-based stress detection using AI and IoT is feasible.
- AI-enhanced PID provides adaptive and user-specific ambient control.
- The system offers scalability and low energy consumption.

5.2. Limitations

- EEG headsets require user calibration and clean signal acquisition.
- Wi-Fi dependency may reduce reliability in weak signal areas.
- Stress dynamics may require deeper AI models such as LSTM.

6. Conclusion and Future Work

This study presents a smart, portable system for mental stress detection and mitigation using AI-enhanced PID control and EEG monitoring. The system autonomously adjusts environmental factors in response to neural feedback, offering a practical solution for stress reduction in real-time.

Future developments will include:

- Integration of deep learning models for richer emotional classification.
- Inclusion of other physiological signals (heart rate, GSR).
- Expanded user dashboard and multi-user adaptability.

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