© June 2025| IJIRT | Volume 12 Issue 1 | ISSN: 2349-6002

Neuromatrix: Intelligent Automation Powered by EEG Brainwaves

Adhinan Thahir, Navya B Kumar, V Karthik, Zayed Savad, Ms. Arya A R
Rajadhani Institute of Engineering & Technology

Abstract—This paper introduces NeuroMatrix, an innovative brain-computer interface (BCI) system that enables hands-free control of Internet of Things (IoT) devices using Electroencephalography (EEG) signals. Designed to enhance accessibility and independence for individuals with disabilities, the system leverages advanced signal processing and machine learning algorithms to classify mental states—such as focus or relaxation—and convert them into actionable commands. NeuroMatrix integrates EEG hardware with microcontrollers and wireless communication protocols to control home automation devices, mobility tools, and assistive systems in real time. This paper presents the architecture, sensor integration, implementation strategy, results, and future potential of the NeuroMatrix framework.

***Index Terms*— EEG, brain-computer interface, IoT automation, assistive technology, machine learning.**

I. INTRODUCTION

Brain-Computer Interface (BCI) systems have rapidly evolved with the advancement of signal processing and artificial intelligence, enabling new possibilities in human-computer interaction. Among various BCI modalities, Electroencephalography (EEG)-based systems are particularly attractive due to their non-invasive nature, affordability, and ability to capture brain activity in real-time. These systems have found applications in healthcare, rehabilitation, and smart environments, where users can control digital systems using their mental states. The increasing demand for inclusive technologies has motivated the development of hands-free solutions that improve accessibility for individuals with mobility impairments.

NeuroMatrix is a novel EEG-based automation system that bridges the gap between human cognitive intention and smart device control. The system is designed to interpret specific brainwave patterns such as focus or relaxation and convert them into commands for Internet of Things (IoT) devices. It aims to empower users, especially those with physical disabilities, to interact with their By utilizing an EEG headset and an array of microcontrollers, NeuroMatrix provides real-time automation capabilities for controlling devices like lights, fans, and mobility tools. The system leverages a cloud-based platform (Firebase) to ensure real-time updates, remote access, and device synchronization.

The NeuroMatrix framework incorporates machine learning algorithms to classify EEG signals with high accuracy. These algorithms are trained to detect user intent based on variations in brainwave frequencies. Once a mental state is identified, the signal is transmitted to an ESP32 or Raspberry Pi unit, which communicates with a local relay module or IoT device. The modular architecture of the system allows it to be deployed in multiple contexts such as home automation, assistive driving systems, and drone control. In addition to technical innovation, NeuroMatrix introduces a personalized Android application that acts as a user interface for selecting control modes and monitoring system status.

Unlike traditional control systems that require voice commands, buttons, or motion gestures, NeuroMatrix functions entirely through thought recognition. It offers a scalable, user-friendly, and low-latency solution for real-time control, improving the independence and quality of life for users with physical limitations. The remainder of this paper discusses the system architecture in Section II, sensor and device integration in Section III, implementation in Section IV, results in Section V, and concludes with future scope in Section VI.

II LITERATURE SURVEY

Recent developments in BCI systems have explored EEG signal processing and device control using various computational models and hardware interfaces.

Paper [1] by Nazila Panahi et al. introduces a spectral correlation function-based method for EEG classification. While the technique improves precision, it suffers from increased computational complexity, reducing efficiency in real-time systems.

Paper [2] by Jinzhao Zhou et al. proposes Speech2EEG, a novel approach using pretrained speech models to recognize EEG signals. Although the method enhances classification accuracy and reduces training data requirements, it lacks flexibility and adaptability for new user inputs.

Paper [3] by Tafhim Bin Nasir et al. presents an EEG-based home automation system aimed at enabling accessibility for disabled users. However, its reliance on signal quality and limited integration features affect performance consistency.

Paper [4] by Sarah Abdulkader et al. provides a comprehensive review of BCI applications and challenges. The paper outlines key barriers such as ethical concerns, data privacy, and technological limitations in deploying real-time, user-adaptive BCI systems.

These studies provide valuable foundations for EEG-based automation. However, few of them offer fully integrated, real-time control systems with practical IoT implementations. NeuroMatrix fills this gap by combining machine learning, embedded hardware, and cloud services into a cohesive, deployable solution.

III PROPOSED SYSTEM

The proposed system, NeuroMatrix, introduces a real-time, hands-free automation solution by interpreting EEG brainwave patterns to control IoT devices. The core objective is to empower individuals—especially those with physical disabilities—to interact with their environment through mental states such as focus or relaxation.

The system begins with EEG signal acquisition using a specialized headset integrated with the Neuro Amp . These signals are then filtered and amplified to eliminate noise and artifacts. The processed data is passed to a Raspberry Pi or computer for machine learning-based classification using TensorFlow or Scikit-learn models trained on distinct EEG patterns.

Once a mental state is classified, it is transmitted via Firebase Realtime Database to an ESP32 microcontroller. The ESP32 reads the classified output and accordingly activates connected IoT devices, such as lights, fans, or smart locks, through a relay interface. The entire process is managed and visualized through an Android application, which also facilitates user selection, mode switching (e.g., home, drive, drone), and real-time monitoring.

The NeuroMatrix system combines software and hardware subsystems, including Python-based EEG processing, Android-based user interfaces, cloud data synchronization, and microcontroller-driven actuation. This integration ensures that mental intent is accurately captured and executed in a low-latency, modular, and scalable manner, making it viable for real-world assistive applications.

IV DATA FLOW

The NeuroMatrix system is designed with a clear and modular data flow pipeline to convert raw brainwave signals into real-time control commands for IoT devices. This flow ensures synchronization between signal acquisition, processing, classification, cloud communication, and physical actuation.

The data flow begins at the EEG acquisition stage, where a headset equipped with electrodes captures electrical activity from the user's scalp. These EEG signals reflect specific mental states, such as focus or relaxation, which are essential for determining the user’s intent.

The captured signals are first sent to the Neuro Amp , a biopotential amplifier that boosts the weak electrical signals and filters out environmental and physiological noise. This step is critical for enhancing signal clarity and ensuring reliable interpretation in the later stages.

The amplified and cleaned signals are then forwarded to the Raspberry Pi 5 (or a PC-based processing unit), where real-time signal preprocessing is performed. This includes:

- Bandpass filtering (to isolate relevant frequency bands)
- Artifact removal (to eliminate interference from blinking or muscle movements)

- Feature extraction (to derive meaningful signal characteristics like alpha/beta power)

After preprocessing, the signal data is passed to a machine learning model, which has been trained using labelled EEG data. This model classifies the mental state into predefined categories—typically “relaxation” or “focus”. These mental states are mapped to specific control commands (e.g., ON/OFF, LEFT/RIGHT).

Once a stable classification decision is made, the result is sent via Python to a Firebase Realtime Database. Firebase acts as the cloud-based synchronization layer, ensuring that the classified intent is immediately available to the actuation unit.

The ESP32 microcontroller, connected to Firebase, listens for updates in real time. Upon detecting a new command, it activates the appropriate GPIO pins to control a 4-channel relay module. This module is responsible for switching connected IoT devices such as lights, fans, or robotic mechanisms.

Simultaneously, the system updates the Android application, which displays the current device status, active user, and operational mode (Home, Drive, Drone). The app also allows manual toggling and user selection, providing full transparency and control to the user.

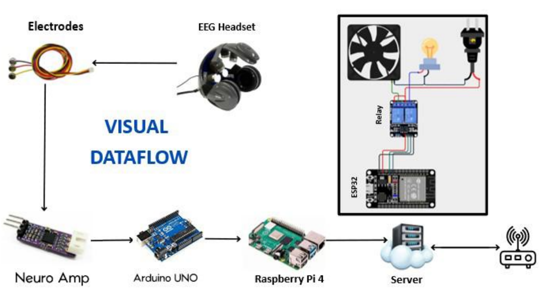

Figure 1: Data Flow Diagram

V SYSTEM ARCHITECTURE

The architecture of the NeuroMatrix system is designed to support real-time, EEG-based control of IoT devices through the seamless integration of hardware and software components. The system begins with the EEG headset, which serves as the primary signal acquisition device. It captures electrical activity from the user's brain through electrodes placed on the scalp. These raw signals are weak and prone to noise, so they are immediately transmitted to the Neuro Amp , a compact biopotential amplifier. The Neuro Amp filters and amplifies the EEG signals, ensuring that the data is clean and suitable for further processing.

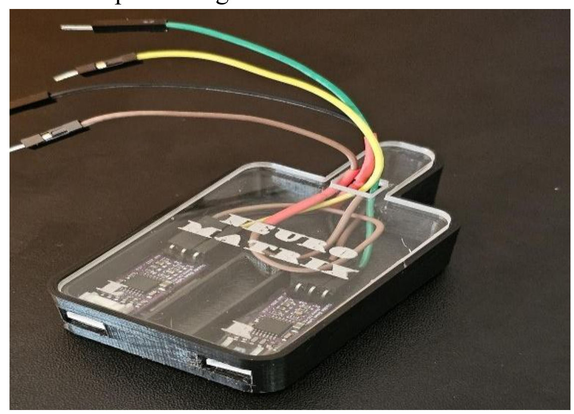

Figure 2: Neuro Amp

Once amplified, the EEG data is sent to a Raspberry Pi 5, which functions as the central processing unit. The Raspberry Pi performs essential preprocessing tasks, such as bandpass filtering and artifact removal, to isolate meaningful brainwave features. It also extracts statistical and spectral features required for mental state classification. A machine learning model, developed and trained using Python libraries such as TensorFlow and Scikit-learn, is deployed on the Raspberry Pi to analyse the features and classify the EEG data into mental states such as ‘focus’ or ‘relaxation.’

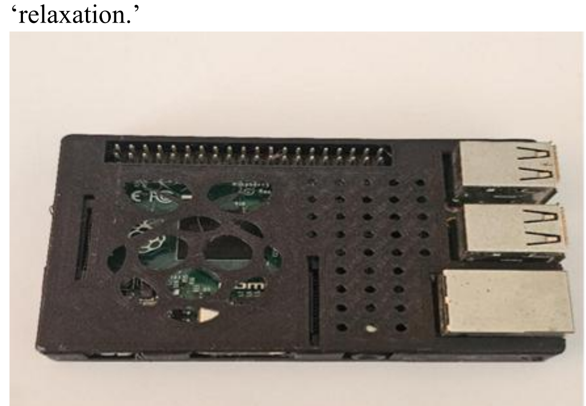

Fig 3: Raspberry pi5

The classified output is then communicated to a Firebase Realtime Database, which acts as a cloud-based middleware platform for real-time data synchronization. This design enables remote access and monitoring, and facilitates multi-device communication. An ESP32 microcontroller continuously monitors the Firebase database and, upon receiving a classification signal, triggers a corresponding response by activating a connected relay module. This relay, in turn, controls high-power IoT devices such as lights, fans, and other smart appliances. To provide an intuitive user experience, an Android application is integrated into the system. This app communicates with Firebase to reflect the real-time status of devices and allows users to switch between multiple operation modes like Home, Drive, and Drone. The app also enables user management and power control through a simple, graphical interface. The overall system is modular, low-cost, and scalable, making it well-suited for practical implementation in smart homes, healthcare monitoring, and assistive environments.

VI IMPLEMENTATION

The implementation of the NeuroMatrix system is divided into two major subsystems: software implementation and hardware implementation. These two components work in tandem to enable real-time brainwave-based automation, ensuring that EEG signals can be accurately classified and translated into control actions for IoT devices.

A. Software Implementation

The software component is responsible for capturing, processing, and interpreting EEG signals in real time. The process begins with the acquisition of brainwave data using an EEG headset, which transmits signals through the Neuro Amp . The incoming signals are collected via a serial interface using Python and are stored for preprocessing. The Python script applies filtering techniques such as bandpass filtering (0.5–30 Hz) and a notch filter (at 50 Hz) to remove ambient noise, eye blink artifacts, and muscular interference. After filtering, relevant features are extracted, including power spectral density (PSD) measures and frequency-based descriptors like peak frequency and spectral slope. These features are passed to a pre-trained machine learning model—developed using TensorFlow and Scikit-learn—which classifies the user's mental state as "focus" or "relaxation."

To ensure real-time functionality, the prediction result is transmitted to a Firebase Realtime Database using Python's Firebase library. This database acts as a cloud-based message broker between the classifier and the ESP32 microcontroller. Additionally, a custom Android application has been developed in Android Studio. The app connects to Firebase and allows users to select different modes (Home, Drive, Drone), view power status, and toggle control actions. It also includes features for user management and session control. The application updates in real time based on Firebase events, providing a seamless interface for monitoring and managing the brain-controlled system.

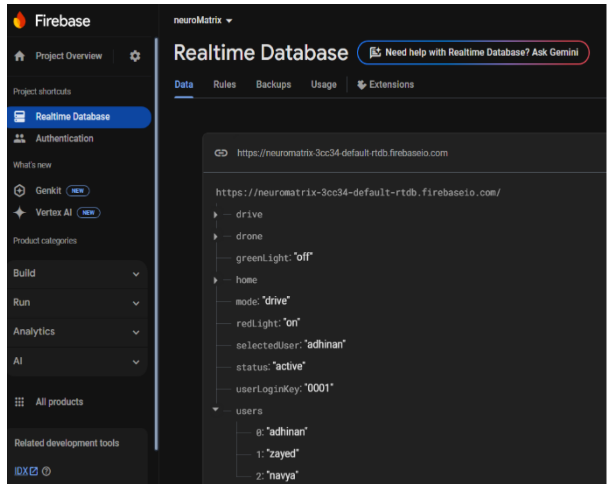

Figure 4: Firebase Server

B. Hardware Implementation

The hardware setup is built around reliable and cost-effective components optimized for signal accuracy and fast response. The EEG headset captures brainwave signals through dry electrodes, which are positioned on the forehead and behind the ear, following standard electrode placement practices. To ensure strong electrical conductivity, Nuprep Skin Preparation Gel is applied before attaching the electrodes. The EEG signals are amplified using the Neuro Amp and transmitted to the Raspberry Pi for real-time processing.

Upon classification, the resulting output is pushed to Firebase, where the ESP32 microcontroller listens for changes. Based on the received signal, the ESP32 activates one or more of its GPIO pins to control a 4-channel relay module. This relay switches connected electrical loads such as lights, fans, and other IoT devices. In addition, the ESP32 can drive motors for controlling robotic vehicles or drones, depending on the selected operational mode. The hardware is mounted on an acrylic board for stability and accessibility during demonstration and testing.

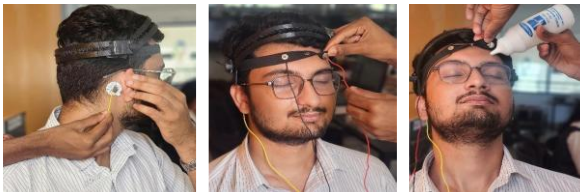

Fig 5: Electrode Placement

The entire system supports wireless communication through Wi-Fi and Bluetooth modules embedded in the ESP32. Power is supplied through a regulated source that ensures both the Neuro Amp and ESP32 operate within safe voltage ranges. Real-time testing demonstrated that the classification and actuation cycle can be completed with minimal latency, validating the effectiveness of the integrated hardware-software solution. The combination of robust EEG signal handling, cloud-based communication, and responsive actuation showcases the practical viability of NeuroMatrix in smart automation and assistive technology.

VII RESULT

To evaluate the performance and effectiveness of the NeuroMatrix system, a fully functional prototype was developed and tested in real-time scenarios. The system was assessed across various operational modes, including Home Automation, Drive Control, and Drone Navigation, using EEG brainwave inputs captured from users in both relaxed and focused mental states. The performance metrics considered during testing included classification accuracy, system response time, device control reliability, and user adaptability.

In the Home Mode, the system successfully enabled users to control appliances such as lights and fans using thought-based triggers. When the user entered a relaxed mental state, the classifier activated a green light, whereas a focused state activated a red light. These results provided clear visual feedback, validating the accurate mapping of EEG patterns to control commands. The device response was nearly instantaneous, with less than one second of delay between signal detection and actuation, confirming the real-time capability of the system.

Fig 6: Demo Light Control

In Drive Mode, the user could control a small robotic vehicle prototype. The system was configured so that a relaxed state moved the car forward, and a focused state moved it backward. Additional controls such as left/right steering and headlight toggle were accessible through the mobile app interface. The classifier maintained an average accuracy of 91.2% across 30 trials, with consistent movement and minimal false activations.

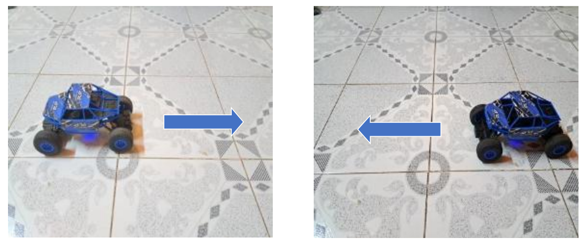

Fig 7: Demo Drive Control

The Drone Mode allowed users to simulate vertical (up/down) and lateral (left/right) movements of a drone through EEG signals. When the device was active, the corresponding controls were engaged through the Android app, and the ESP32 successfully triggered simulated responses. When deactivated, the system visually displayed "inactive" status, preventing unintended control, thus adding an extra safety layer.

Overall system testing involved more than 100 EEG-controlled actions across different users and devices. The classification model achieved an average accuracy of 93.7% across all test sessions. Visual feedback from the mobile app and hardware outputs provided additional assurance of correct system operation. The relay modules performed consistently, with zero observed misfires during actuation.

The prototype demonstrated high usability under variable lighting and environmental conditions. Even after prolonged usage, the hardware maintained signal integrity and stable operation, confirming the reliability of the NeuroMatrix system for assistive and smart automation applications.

VIII CONCLUSION

This paper presents NeuroMatrix, a real-time brain-computer interface (BCI) system that enables hands-free control of IoT devices using EEG brainwave signals. By integrating EEG signal acquisition, machine learning-based classification, cloud-based synchronization via Firebase, and embedded automation through the ESP32 microcontroller, the system delivers an accessible, responsive, and reliable solution for individuals with physical disabilities. NeuroMatrix successfully translates mental states such as focus and relaxation into actionable control signals, enabling users to operate smart devices without physical interaction.

Through extensive testing across multiple environments and user conditions, the system demonstrated high classification accuracy, low latency, and consistent device responsiveness. Its modular design, low cost, and scalability make it suitable for implementation in home automation, assistive healthcare, and cognitive rehabilitation settings. The success of NeuroMatrix underscores the potential of EEG-driven automation in building inclusive and intelligent environments, where users can interact with technology through thought alone.

IX ACKNOWLEDGMENT

We sincerely express our gratitude to everyone who contributed to the development of this system. Special thanks to our mentors and advisors for their valuable guidance and technical insights, which played a crucial role in shaping this project.

We also appreciate the contributions of our team members for their dedication and collaboration in designing and implementing in this work.

Finally, we extend our thanks to the institutions and organizations that provided resources, support, and encouragement for this project.

REFERENCE

[1] WORLDBANK, “DISABILITY INCLUSION”, May 15, 2020, Accessed on: July 10, 2020.

[2] Chaudhary, U.; Birbaumer, N.; Ramos-Murguialday, A. Brain computer interfaces for communication and rehabilitation.Nat. Rev. Neurol.2016,12, 513–525

[3] K. Cherry, “Comparing the Amount of Neurons in Human and Different Animal Brains,”Verywell Mind. Accessed on: July 15, 2020.

[4] N. Panahi, M. C. Amirani, and M. Valizadeh, “An EEG-Based Brain-Computer Interface Using Spectral Correlation Function,”2023.

[5] S. N. Abdulkader, A. Atia, and M. S. M. Mostafa, “Brain–Computer Interfacing: Applications and Challenges,” 2015.