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DESIGN AND DEVELOPMENT OF BCI BASED SMART WHEELCHAIR

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Abstract—Brain Computer Interface (BCI) technology enables direct communication between the human brain and external devices by translating neural activity into control commands. This paper presents the design and development of a low cost BCI-based smart wheelchair intended to assist individuals with severe motor disabilities. The proposed system utilizes electroencephalography (EEG) signals acquired from the scalp to detect user intent and convert it into real-time wheelchair motion commands. An embedded control unit based on an Arduino microcontroller processes the classified EEG signals and controls the wheelchair motors through an L298N motor driver. To enhance user safety, ultrasonic sensors are integrated for obstacle detection and emergency stopping. The developed prototype demonstrates reliable hands-free navigation with a cost-effective and scalable architecture, making it suitable for assistive mobility and rehabilitation applications.

Index Terms—Brain-Computer Interface (BCI), Electroencephalography (EEG), Smart Wheelchair, Assistive Technology

I. INTRODUCTION

Independent mobility is a fundamental requirement for maintaining quality of life, dignity, and social participation. However, individuals suffering from severe motor impairments caused by spinal cord injuries, stroke, amyotrophic lateral sclerosis (ALS), cerebral palsy, or advanced neuromuscular disorders often face extreme difficulty in operating conventional wheelchairs. Traditional electric wheelchairs typically rely on joysticks, switches, or touch-based interfaces, which require residual muscular control. For patients with quadriplegia or advanced paralysis, these interfaces are either inefficient or entirely unusable, leading to complete dependence on caregivers for mobility assistance. By creating a direct line of communication between the human brain and external equipment, Brain-Computer Interface (BCI) technology offers a possible answer. Bypassing traditional neuromuscular routes, a BCI system reads brain activity and translates it into control signals. Because of its mobility, affordability, high

temporal resolution, and suitability for real-time applications, electroencephalography (EEG) is the most commonly used neuroimaging technique for non-invasive BCI systems. EEG signals are perfect for assistive control systems because they show dynamic brain activity linked to cognitive states like concentration, relaxation, motor imagery, and intention. Recent developments in signal processing and machine learning have greatly enhanced the functionality of BCI systems based on EEG. Supervised learning algorithms enable more accurate classification of mental states and facilitate the identification of subtle patterns in noisy EEG data. Despite these developments, a large number of BCI-based wheelchair systems still in use rely on intricate multi-class motor imagery paradigms that are cognitively taxing and require a great deal of user training. These systems frequently have poor long-term usefulness, low flexibility, and excessive latency, especially for older or cognitively impaired users. These limitations highlight the need for simpler, more efficient, and user-friendly BCI-based assistive mobility solutions.

II. LITERATURE SURVEY

Krishna Rao et al., [1] developed a non-invasive Brain-Computer Interface (BCI)-based smart wheelchair using EEG signals captured through a Brainsense headset. The system utilized artifact signals such as eye blinks and jaw movements for directional control. MATLAB was used for signal processing, while Arduino interfaced with a motor driver to enable wheelchair navigation. The proposed system demonstrated effective indoor mobility support for patients with locked-in syndrome.

Shashidhar et al., [2] proposed an EEG-based smart wheelchair implemented using Raspberry Pi for elderly and paralyzed patients. EEG signals were acquired via a Brain-Sense headset and transmitted through Bluetooth for processing. The system incorporated ultrasonic sensors for obstacle

detection and remote accessibility features. Experimental results showed improved real-time responsiveness and enhanced independent mobility.

A BCI-controlled smart wheelchair designed for patients with Amyotrophic Lateral Sclerosis (ALS) utilized an EMO-TIV Insight headset to capture EEG signals and convert mental commands into movement directions. The processed signals were communicated via Bluetooth to a microcontroller-based unit, enabling independent navigation and improved quality of life, as demonstrated by Espiritu et al., [3].

Ngo et al., [4] proposed a semi-automatic smart electric wheelchair controlled by EEG signals integrated with a graphical user interface (GUI). Eye-blink detection was performed using threshold-based peak detection and bandpass filtering techniques. The GUI allowed users to select predefined destinations, reducing cognitive workload during continuous operation. Experimental validation demonstrated improved safety and usability in indoor environments.

To improve control reliability, a hybrid BCI-based wheelchair combining EEG and EOG signals has been developed. This approach enhanced command accuracy and reduced false activations compared to single-modal systems. Stable navigation control was achieved through signal processing and classification techniques, as reported by Chawda et al., [5].

An Arduino-based wheelchair controller utilizing eye-blink detection has been proposed as a low-cost assistive solution. EEG signals were transmitted via Bluetooth for real-time processing, enabling directional control without requiring voluntary muscular movement. The system demonstrated accessibility and practicality for individuals with locomotor disabilities, as presented by Gupta et al., [6].

Lakas et al., [7] suggested a cloud-based wheelchair that can be controlled by the brain and can move on its own using P300 EEG signals. The system takes brain signals, processes them, and sends them to a cloud platform to make decisions and do calculations. The wheelchair uses BCI commands and sensors built into the chair to make sure it can safely move around. This method makes processing more efficient and helps people with severe disabilities move around safely.

A hybrid system known as Cognitive-Chair combines EEG and EOG signals to improve command accuracy and reliability. Machine learning algorithms are used to interpret user intent and translate it into directional movement, providing a more user-friendly solution for individuals with limited motor abilities, as developed by Joshi et al., [8].

A comprehensive review of EEG-based BCI wheelchair systems has examined various signal acquisition techniques, feature extraction methods, and classification approaches. It also highlights hardware configurations and key challenges such as noise, accuracy, and real-time implementation, as discussed by Limchesing et al., [9].

An EEG-based wheelchair system utilizing the Adaptive Neuro-Fuzzy Inference System (ANFIS) has been proposed to improve navigation accuracy. The system integrates EEG signal processing with image processing techniques and employs a Raspberry Pi for control, resulting in enhanced assistive

mobility performance. This approach was developed by Turnip et al., [10].

Despite significant advancements in EEG-based BCI wheelchair systems, several limitations persist across existing approaches. Many systems rely on complex signal processing techniques, hybrid modalities, or multi-class control strategies that increase computational complexity and user training requirements. Additionally, issues such as latency, reduced real-time performance, and limited adaptability for continuous usage remain critical challenges. These limitations highlight the need for a simpler, efficient, and real-time BCI framework that can provide reliable assistive mobility with minimal cognitive load. These limitations highlight the need for a simple, efficient, and real-time BCI-based assistive mobility system. To address this, the proposed work presents an EEG-based framework that classifies user intent into two mental states and translates it into control commands for wheelchair navigation.

III. METHODOLOGY

This work presents the design and implementation of an EEG-based Brain Computer Interface (BCI) system for assistive mobility applications. The proposed system aims to provide a simple and efficient mechanism for translating user intent into control actions with minimal cognitive effort. The system architecture is represented using a block diagram, as shown in Fig. 1, depicting the overall workflow.

A. Electrodes

The main sensing component of the proposed BCI-based smart wheelchair system is the EEG electrodes. To record electrical potentials produced by synchronised neuronal activity in the cerebral cortex, these electrodes are non-invasively applied to the frontal cortex of scalp. The recorded EEG signals are extremely sensitive to noise and outside interference, and they usually fall into the microvolt range. The electrodes in the suggested system continuously record brain signals that correspond to two mental states: relaxed and attentive. For the purpose of differentiating these states, variations in the alpha and beta frequency bands are especially important. Proper electrode placement, stable skin contact, and minimal motion artefacts are crucial because the accuracy of the entire system depends on the integrity of the acquired EEG signals [1], [9]. EEG signals are characterized by low amplitude, typically in the microvolt range, and are highly susceptible to noise caused by eye blinks, muscle movements, and power-line interference. To minimize these effects, the subject was seated comfortably in a controlled environment during data collection. Multiple EEG samples were collected for both mental states to ensure variability and improve generalization of the trained model.

B. BCI Module Interface

The signal acquisition system and processing unit are connected by the BCI module interface. Weak EEG signals are amplified, filtered, and transformed into a digital format that can be used. The BioAmp EXG Pill and Arduino UNO

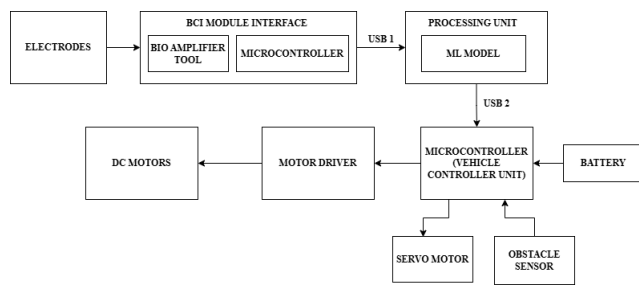


Fig. 1. Block diagram

manage signal conditioning, digitisation, and transmission in this project, guaranteeing precise and dependable system performance.

1) *Bio-Amplifier Tool (Bio Amp EXG Pill)*: The Bio Amp EXG Pill is used as the signal amplification and conditioning module in the suggested BCI-based smart wheelchair system. Digital systems are unable to directly process EEG signals obtained from scalp electrodes due to their extreme weakness and microvolt range. Because of its high input impedance and low noise amplification, the Bio Amp EXG Pill which is intended for biopotential signal acquisition such as EEG, EMG, and ECG is appropriate for sensitive neural recordings.

The suggested system uses built-in filtering to reduce electrical interference and motion artifacts while amplifying raw EEG signals to a detectable level while maintaining waveform characteristics. The EXG Pill guarantees dependable EEG data for precise feature extraction and mental state classification in later stages by boosting signal stability and signal-to-noise ratio.

2) *Arduino R4 Minima Microcontroller*: The crucial task of transforming biological signals into digital data that can be used is handled by the Arduino R4 Minima, which serves as the main control unit in the BCI module interface. This system uses a high-performance ARM Cortex-M4 processor to process conditioned EEG signals from the bio amplifier before preparing the data for USB transmission to the processing unit. It can effectively handle real-time signal acquisition and simple filtering thanks to its increased clock speed, larger memory capacity, and improved precision over previous boards. It is a dependable link between brain signal acquisition and intelligent decision-making in the wheelchair control system because it also guarantees steady communication between the hardware components and the machine learning model.

C. Processing Unit

The processing unit is the core component that analyzes EEG signals and generates control commands. In this project, a PC is used for its high processing power and ease of development. Using Python and libraries like NumPy and Scikit-learn, it performs noise removal, feature extraction, and classification to enable real-time decision-making. The PC or Raspberry Pi

serves as the system's central signal processing unit. The EEG signals are digitised and sent to this computational platform for additional processing after they have been amplified and conditioned. To improve signal reliability at this point, extra preprocessing methods like segmentation, normalisation, and artefact reduction are carried out.

Feature extraction plays a critical role in distinguishing between attentive and relaxed mental states. Features were derived from EEG frequency bands associated with cognitive activity, including alpha and beta rhythms. Statistical and spectral features were computed from each EEG segment to capture variations in signal amplitude and frequency content. Extracted features were assembled into feature vectors and labeled according to their corresponding mental state. This labeled dataset formed the basis for supervised machine learning. Feature selection was performed to reduce dimensionality and eliminate redundant information, thereby improving classifier efficiency and reducing computational load during real-time operation.

Following feature extraction, a supervised machine learning approach was employed to classify EEG signals into two cognitive states: attentive and relaxed. The choice of a supervised classifier was motivated by its ability to learn discriminative patterns from labeled EEG data and provide reliable predictions during real-time operation. Each extracted feature vector was associated with a corresponding class label, where Class 1 represented the attentive state and Class 0 represented the relaxed state.

During the training phase, the dataset was divided into training and validation subsets to evaluate the generalization capability of the classifier and prevent overfitting. The classifier parameters were optimized to achieve a balance between classification accuracy and computational efficiency, which is essential for real-time BCI applications. Performance metrics such as classification accuracy and prediction consistency were used to assess model effectiveness. Once trained, the classifier was deployed in an online inference mode. Incoming EEG signals were continuously processed, and the trained model generated predictions in real time. The binary classification framework reduced decision complexity and improved robustness against noise and signal variability. This approach also minimized user training time, making the system more accessible for individuals with limited cognitive endurance [1], [8].

Overall, the comparison presented in Table I across three EEG datasets: The collected dataset, The Wheelchair EEG Signals dataset¹ and The EEG Brainwave Dataset: Feeling Emotions² demonstrates the classification performance of various machine learning models, including Support Vector Classifier (SVC), K-Nearest Neighbors (KNN), Random Forest, Decision Tree, Logistic Regression, Gradient Boosting, and Multilayer Perceptron (MLP). The results indicate that Gradient Boosting achieves the highest accuracy on the collected

¹<https://www.kaggle.com/datasets/mneebahmd/wheel-chair-eeeg-signals>

²<https://www.kaggle.com/datasets/birdy654/eeeg-brainwave-dataset-feeling-emotions>

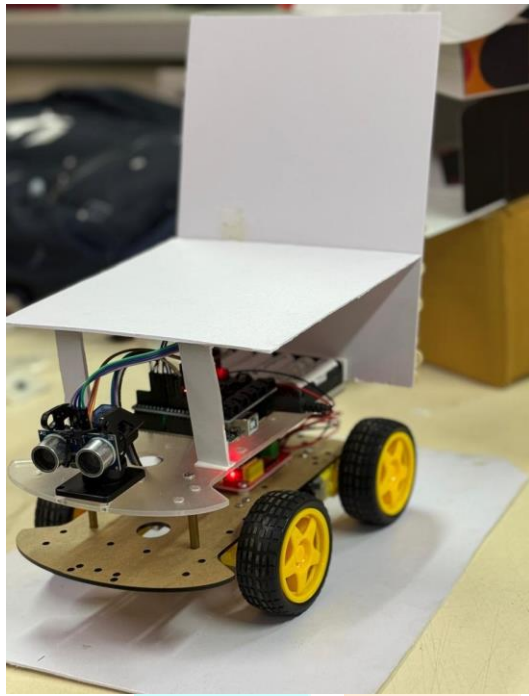


Fig. 2. Experimental Setup

dataset, while Random Forest consistently delivers strong performance across all datasets, highlighting the importance of selecting appropriate models for EEG-based classification tasks, particularly in brain-computer interface applications.

D. Arduino Uno Microcontroller

The Arduino Uno serves as an intermediary control unit that converts high-level movement commands into low-level hardware signals. It is situated between the processing unit (PC) and the motor driver. The processing unit determines the user's intended motion such as forward, left, right, or stop by analysing the EEG signals and running the machine learning model. These choices are sent as serial data via USB communication to the Arduino Uno.

The Arduino Uno interprets these commands by comparing the incoming data with preprogrammed control logic. The Arduino uses its digital I/O pins to produce the proper output signals based on the recognised command. These signals are structured electrical inputs that the motor driver needs, not simple commands.

The Arduino combines digital signals with pulse width modulation (PWM) to power the motor driver. While PWM signals control the motor's speed, digital signals control the motor driver's input pins to determine the motor's rotation direction. These low-power signals from the Arduino are then amplified by the motor driver into high-power outputs that can power the DC motors.

In order to ensure precise and effective execution of user-intended movements, the Arduino Uno acts as an essential interface between software-level decision-making in the processing unit and hardware-level actuation in the motor system.

E. Battery

A rechargeable lithium-ion battery powers the system, allowing for portability and autonomous operation without the need for an external power source.

Depending on the system configuration and motor requirements, the battery usually provides a voltage of 7.4V or 12V. The BioAmp EXG Pill, Arduino UNO, sensors, and motor driver are all powered by the battery. In order to preserve stable operation and safeguard delicate components, proper voltage regulation is ensured. Because of their long life cycle, high energy density, and lightweight design, lithium-ion batteries are favoured. Because of this, the system is portable and appropriate for practical uses.

F. Ultrasonic Sensor

An HC-SR04 ultrasonic sensor is integrated into the suggested system to improve user safety by detecting obstacles in real time. The sensor uses the time-of-flight principle, which involves sending out high-frequency ultrasonic pulses (about 40 kHz) and receiving the reflected echo from an obstruction.

Using the conventional sound propagation formula, the Arduino microcontroller calculates the distance by measuring the time difference between transmission and reception. The sensor in the suggested architecture keeps an eye on the wheelchair prototype's frontal region.

The microcontroller overrides the forward motion command and initiates a stop condition if an object is detected within a predetermined threshold distance, which is approximately 20 cm. This mechanism enhances the BCI-controlled wheelchair system's dependability and safety by preventing collisions in conjunction with the motor control logic [7].

G. Servo Motor

The system is perfect for sensor positioning and directional adjustments because it uses a servo motor to precisely control angular movement. A servo motor allows precise positioning because it moves within a set range, typically 0° to 180°, in contrast to DC motors that rotate continuously. Pulse Width Modulation (PWM) signals from the Arduino microcontroller are used to power it. The servo shaft's rotational angle is determined by the width of the PWM signal. This makes it possible for the Arduino to precisely and smoothly control the servo position. Additionally, servo motors have an internal feedback system that keeps them in the intended position even when the load varies. In order to search for obstacles, the servo motor in this system rotates the ultrasonic sensor. In this system, the servo motor helps rotate the ultrasonic sensor to scan for obstacles. Its compact size, low power consumption, and high accuracy make it suitable for robotic applications.

H. Motor Driver

Between the microcontroller and the DC motors, the motor driver module serves as the power interface. The L298N H-bridge driver amplifies the low-current digital signals produced by the Arduino, which are insufficient to drive the motors

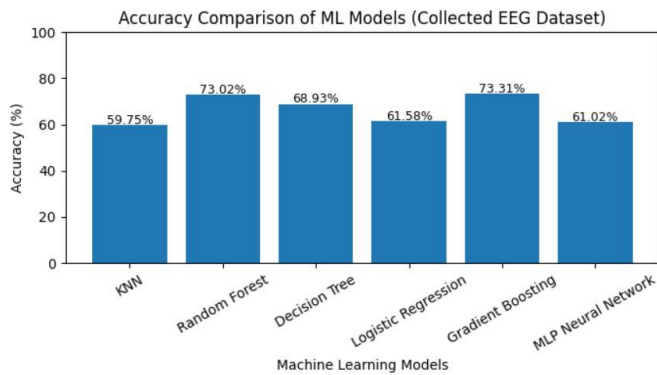


Fig. 3. Accuracy comparison

directly. It then switches the polarity of the voltage to control motor direction.

Multidirectional motor control, enabling forward, left, and right movement along with stop functionality is made possible by the H-bridge configuration. Additionally, the driver uses PWM signals from the microcontroller to control motor speed. Stable power delivery and effective mechanical motion control are guaranteed by this module [2].

I. DC Motors

The DC geared motors make up the system's last actuation stage. The wheelchair prototype can move thanks to these motors, which transform electrical energy from the motor driver into rotational mechanical motion. Enough torque is supplied by the geared mechanism to enable steady and regulated mobility. Neural activity recorded from the user's brain is finally converted into the assistive mobility platform's actual displacement during this last phase.

TABLE I
COMPARISON OF MACHINE LEARNING MODELS ON DIFFERENT EEG DATASETS

Model	Collected (%)	Existing 1 (%) ¹	Existing 2 (%) ²
SVC	67.21	70.38	77.78
KNN	59.75	65.16	66.67
Random Forest	73.02	69.34	77.78
Decision Tree	68.93	64.46	44.44
Logistic Regression	61.58	64.11	77.78
Gradient Boosting	73.31	69.86	44.44
MLP Neural Network	61.02	68.29	66.67

TABLE II
PERFORMANCE OF ML MODELS ON COLLECTED EEG DATASET

Model	Accuracy	Precision	Recall	F1 Score
SVC	0.6721	0.6460	0.7768	0.7054
KNN	0.5975	0.6046	0.5975	0.5974
Random Forest	0.7302	0.7303	0.7302	0.7303
Decision Tree	0.6893	0.6910	0.6893	0.6897
Logistic Regression	0.6158	0.6291	0.6158	0.6141
Gradient Boosting	0.7331	0.7335	0.7331	0.7332
MLP Neural Network	0.6102	0.6228	0.6102	0.6086

IV. RESULT AND DISCUSSION

This study presents the design and development of a low-cost, real-time EEG-based BCI smart wheelchair prototype. The gadget enables hands-free mobility by translating brain signals into control commands. A supervised machine learning model is used to classify EEG data, and the resulting commands are executed by an embedded microcontroller. By incorporating obstacle detection, operational safety is increased. The proposed system demonstrates a simple, efficient, and scalable technique for assistive mobility applications. Future advances could include the addition of more sensory modalities, improved categorisation accuracy, and multi-command control.

EEG signals obtained from the frontal region were continually analysed and categorised in a real-time approach. Reliable user concentration level distinction was made possible by features extracted from the alpha and beta frequency channels. A microprocessor received the classification data and transformed it into orders for the robotic platform to move ahead and stop. During operation, the system demonstrated steady responsiveness and low latency.

An ultrasonic sensor was added to improve system safety by enabling obstacle detection and automated stopping when necessary. Although it restricts directional flexibility, binary control decreased user effort and increased reliability. Overall, the findings provide a viable and affordable method for EEG-based assisted mobility, with room to grow into more sophisticated control schemes and better classification results in the future. The findings, as illustrated in Fig. 3, show that ensemble learning techniques outperform conventional classifiers in most cases. As shown in Table II, Gradient Boosting achieved the highest accuracy of 73.31% in the collected dataset, closely followed by Random Forest with 73.02%. This suggests that ensemble-based methods are successful in capturing the intricate patterns found in EEG signals. For the Wheelchair EEG Signals dataset, Random Forest achieved the highest accuracy of 74.15%, outperforming SVC and Gradient Boosting and on the EEG Brainwave Dataset: Feeling Emotions, SVC, Random Forest, and Logistic Regression achieved the highest accuracy of 77.78%, indicating that different classifiers can perform well depending on the characteristics of the dataset.

V. CONCLUSION

The design and development of a low-cost, real-time EEG-based BCI smart wheelchair prototype are presented in this work. The device converts brain signals into control commands, allowing for hands-free mobility. EEG signals are classified using a supervised machine learning model, and an embedded microcontroller carries out the resulting commands. Operational safety is improved by integrating obstacle detection. A straightforward, effective, and scalable approach for assistive mobility applications is demonstrated by the suggested system. Multi-command control, enhanced classification accuracy, and the incorporation of additional sensory modalities are possible future developments.

VI. FUTURE SCOPE

Although the suggested BCI-based smart wheelchair system lays the groundwork for EEG-controlled assistive mobility, there are a number of improvements that could be made in subsequent research to increase functionality, precision, and practicality. The integration of more advanced machine learning or deep learning algorithms could further enhance classification accuracy and improve user adaptability. Advanced artifact removal methods like Independent Component Analysis (ICA) or adaptive filtering can also improve signal quality by lowering noise brought on by environmental interference and muscle movement. Remote supervision and data logging for clinical evaluation would be possible with the integration of wireless communication modules and IoT-based monitoring systems. Additionally, semi-autonomous navigation and intelligent path planning may be made possible by the addition of camera-based vision systems or LiDAR sensors. With these enhancements, the suggested system could develop into a completely operational, dependable, and user-friendly assistive mobility solution for people with severe motor impairments.

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