Brain Wave Controlled Electric Vehicle Powered by Solar Energy

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Abstract: This paper presents a brainwave and eye-movement–controlled electric vehicle (EV) powered by solar energy, aimed at enhancing mobility for individuals with physical disabilities. The system employs an EEG-based Brain–Computer Interface (BCI) to interpret brain signals and facial movement patterns using a mind-wave headset. These signals are processed and translated into vehicular commands such as forward, reverse, left, and right. To ensure sustainability, the vehicle is powered by solar panels, improving energy efficiency and operational self-sufficiency. Additional features including speed control, object detection, and collision avoidance support safe navigation. Experimental observations indicate that EEG-signal interpretation combined with eye-blink detection provides approximately 95% command accuracy. The proposed solution demonstrates significant potential for assistive mobility, environmental sustainability, and user-centric intelligent transport systems.

Keywords— Brain–Computer Interface, EEG, Eye Movement Control, Solar Power, Electric Vehicle, Assistive Mobility.

I.INTRODUCTION

Brain–Computer Interface (BCI) systems establish a direct communication pathway between the human brain and external devices, enabling users to control machines without requiring physical movement. These systems primarily rely on the electrical activity generated by the brain, captured through Electroencephalography (EEG). EEG-based BCIs have emerged as a transformative technology in assistive mobility, rehabilitation engineering, and neuroprosthetics due to their ability to interpret user intent from neural activity. When combined with machine-learning algorithms and signal-processing techniques, EEG signals can be translated into meaningful control commands for motors, actuators, or electronic devices. However, EEG signals are often weak and prone to noise, which can reduce control accuracy. To address this, hybrid interfaces incorporating eye-movement or facial-muscle activity (EMG) have been introduced, offering improved reliability and an additional layer of user command inputs.

In the proposed system, a hybrid brainwave and eye-movement–controlled electric vehicle is designed to provide hands-free mobility to individuals with severe motor impairments, such as paralysis or neuromuscular disorders. EEG sensors continuously monitor the user's mental activity, extracting patterns related to attention, relaxation, or intentional blinking. In parallel, an EMG-based eye-movement detection module identifies left, right, or double-blink signals, enabling multi-directional vehicle navigation. These combined inputs enhance command differentiation, reduce false detections, and provide the user with smoother and more intuitive control of the vehicle.

To promote sustainability and operational independence, the electric vehicle is powered using solar panels. Solar energy not only reduces the dependency on conventional charging infrastructure but also supports long-duration use, making the system suitable for outdoor mobility. A wireless communication link—implemented using ESP32/ESP8266 and RF communication modules—ensures real-time transmission of decoded brain and eye signals to the vehicle's onboard controller. This wireless architecture enables freedom of movement without limiting cable-based constraints.

Safety is further enhanced through an object-detection module that employs ultrasonic and infrared sensors to detect obstacles in the vehicle's path. Upon identifying a nearby object, the system automatically halts or adjusts the vehicle's path, preventing collisions and ensuring a secure driving experience for the user. Feedback mechanisms, such as LED indicators or LCD displays, provide real-time system status, helping users and caregivers monitor operational conditions.

Overall, this paper presents a comprehensive design and implementation of a solar-powered BCI-controlled electric vehicle that integrates EEG-based intent detection, EMG-driven eye-movement control, wireless communication, and intelligent safety features. The system provides a sustainable, user-centered, and technologically advanced mobility solution tailored for individuals with physical disabilities. Through detailed experimentation and analysis, the proposed work demonstrates the practical feasibility and future potential of BCI-assisted transportation systems.

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II RELATED WORK

Brain–Computer Interface (BCI) systems have been extensively investigated over the past two decades as a means of providing assistive control for individuals with motor disabilities. Numerous research initiatives have explored the feasibility of using EEG signals to operate mobility devices such as wheelchairs, robotic arms, and simple navigation systems. These studies collectively highlight the potential of BCI technology while also revealing critical limitations that restrict widespread adoption.

One of the foundational studies in this domain was conducted by Tanaka et al. [7], who introduced an EEG-based control system for electric wheelchairs using motor-imagery signals. Their work demonstrated that users could intentionally modulate brain activity to initiate basic directional commands such as forward or turn movements. Although the concept proved viable, the system suffered from reduced accuracy due to low signal amplitude, interference from environmental noise, and significant variability across individuals. The researchers noted that continuous training was required for users to achieve stable command recognition, and even then, the response time remained slower than what would be acceptable for safe and real-time operation.

Building on such concepts, Winod and Cheng [8] proposed a next-generation electric mobility solution using advanced neural-pattern analysis techniques. Their model aimed to improve the responsiveness of earlier systems by integrating signal classification algorithms capable of distinguishing multiple mental states. Despite these enhancements, the system continued to face challenges related to latency, limited command bandwidth, and difficulty adapting to fluctuating EEG patterns. The authors emphasized the need for hybrid input mechanisms or additional sensory channels to reduce reliance on a single neural-signal pathway.

Hekmat Manesh et al. [9] presented a comprehensive review of existing brain-controlled vehicle technologies, identifying several recurring limitations across published works. Their analysis emphasized the low signal-to-noise ratio in EEG acquisition, inconsistent performance across users, vulnerability to artifacts such as blinking or muscle movement, and a lack of robust filtering techniques to reliably distinguish user intent. They also highlighted that existing systems often struggle in dynamic real-world conditions, where changing environmental factors may affect sensor accuracy. The review concluded that while BCI-based vehicle control is technically feasible, practical deployment requires significant improvements in signal processing and user-specific adaptability.

In parallel, Arduino-based EEG research efforts [3,4] explored low-cost implementations of brain-signal recognition systems. These works concentrated primarily on pattern visualization and educational demonstrations rather than real-time control applications. While valuable as preliminary explorations, such systems lacked the computational power and accuracy needed for mobility platforms, making them unsuitable for assistive navigation or safety-critical environments.

Recent advancements in hybrid BCI systems have sought to overcome these limitations by combining EEG control with auxiliary inputs such as eye blinks, eye movements, or facial muscle signals. This multimodal approach enhances command reliability by providing secondary confirmation and reducing false detections. Although these hybrid systems represent a significant step forward, they still fall short in terms of comprehensive usability. Notably, existing research rarely addresses sustainability factors, such as integrating renewable energy sources to power mobility devices for extended use.

The current literature lacks an integrated solution that combines EEG-based control, hybrid eye-movement commands, wireless communication, real-time obstacle detection, and a sustainable solar-powered electric vehicle platform. This gap motivates the present work, which aims to deliver a holistic, eco-friendly, and user-centric mobility system by merging BCI technology with solar energy and intelligent navigation modules.

III. METHODOLOGY

A. D a Acquisition

EEG signals are captured through a mind-wave headset and transmitted to an ESP32/ESP8266 microcontroller. Eye movements (left, right, blink) are detected using EMG-based sensors. The combined data enables multiple command states for vehicle control.

B. Signal Processing and Transmission

Brain and eye-movement signals undergo preprocessing to eliminate noise. The ESP32 module digitizes the signals and transmits the interpreted commands via RF or Wi-Fi to the EV control unit. Gesture-based classifications include:

- Concentration/Attention → Move Forward
- Relaxation/Low Activity → Stop
- Left/Right Eye Movements → Turn Left/Right
- Double Blink → Reverse

C. ower Management Using Solar Energy

Solar panels installed on the vehicle convert sunlight into electrical energy, which is managed through a charge controller. Energy is stored in a battery, ensuring uninterrupted operation even during low-light conditions.

D. Command Execution and Motor Control

The receiving ESP32 controls:

- Motor Driver (L298N)
- DC Motors for vehicle movement
- Speed-control signals
- Obstacle-avoidance algorithms

E. Object Detection and Safety

Ultrasonic and IR sensors continuously scan the environment. If an obstacle is detected, the vehicle automatically stops or reroutes to prevent collisions.

F. System Flow

1. EEG + Eye movement signals captured
2. Signals processed and classified
3. Commands transmitted to vehicle
4. Vehicle motion executed
5. Obstacle detection ensures safety
6. Real-time feedback provided

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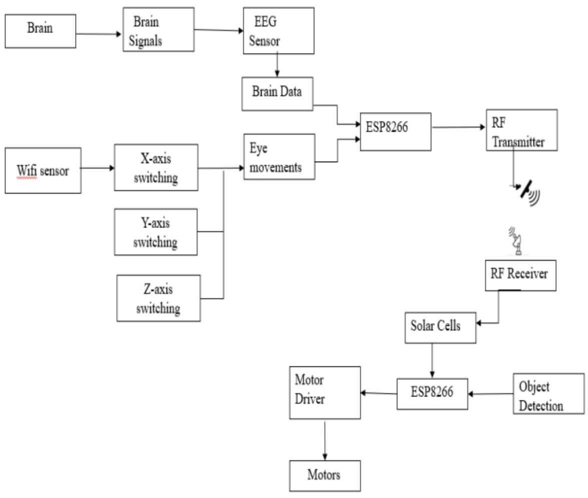

Fig.1. Block Diagram

A. Ha ware Design

The hardware architecture of the proposed system integrates multiple sensing, processing, transmission, and actuation components to enable brain-wave–based electric vehicle control. The brain activity of the user is captured through an EEG sensor, which converts neural signals into measurable electrical data. These signals are forwarded to the ESP8266 microcontroller, which serves as the primary processing unit. Along with brain signals, the user's eye movements—mapped along the X, Y, and Z axes—are detected using a dedicated eye-movement sensing module. These signals act as supporting inputs to improve decision accuracy and enable directional control.

The ESP8266 processes both EEG and eye-movement data and transmits the interpreted commands wirelessly through an RF transmitter. The RF receiver on the vehicle side receives these commands and passes them to a second ESP8266 controller, which handles actuation. Solar panels mounted on the vehicle supply the electrical power required for driving the motors and operating the control electronics, ensuring clean and renewable energy usage.

An ultrasonic object-detection sensor is integrated into the system to prevent collisions. When an obstacle is detected, the ESP8266 overrides user commands and halts the vehicle via the L298N motor driver. The motor driver regulates the speed and direction of the motors according to the commands received. This hardware configuration allows real-time, wirelessly controlled EV movement driven entirely by brain and eye signals.

B. Software Design

The software module of the system is responsible for reading EEG and EMG-based eye-movement signals, classifying them, and converting them into control commands. The ESP8266 firmware is developed using the Arduino IDE with embedded C/C++ libraries to support sensor acquisition, signal filtering, wireless transmission, and motor-control logic.

Software operation begins with continuous sampling of EEG signals and eye movements. The raw EEG data undergoes preprocessing steps such as normalization, threshold filtering, and noise elimination. Eye-movement signals from X, Y, and Z axes are mapped to corresponding directional commands. The system uses predefined thresholds to differentiate between attention levels, blinking patterns, and directional eye cues.

Once the data is classified, the ESP8266 generates one of the following commands: Forward, Left, Right, Stop, or Reverse. These commands are transmitted via RF communication to the receiving ESP8266 module on the vehicle. The receiving module interprets these commands and triggers the motor driver accordingly. Simultaneously, object-detection feedback is monitored; if an obstacle is identified within a predefined distance, the software overrides active commands and forces an emergency stop.

Overall, the software logic ensures robust command recognition, safe operation, and seamless communication between the user interface and vehicle hardware.

C. ystem Flow

The complete operational flow of the brain-controlled electric vehicle is summarized as follows:

1. **System Initialization:**
   The process begins when the system is powered on. The EEG and eye-motion sensing modules start capturing user input.
2. **Signal Acquisition:**
3. The system continuously checks for valid brain-wave signals and eye-movement patterns. If no valid signals are detected, the system remains idle.
4. **Signal Processing:**
   Once EEG or eye-movement inputs are detected, the ESP8266 analyzes the inputs and determines the intended command.
5. **Decision Making:**
   The control algorithm maps the classified signals to one of the available actions:
   a. Move Forward
   b. Turn Left
   c. Turn Right
   d. Stop
   e. Reverse
6. **Command Transmission:**
   The action command is transmitted wirelessly using the RF transmitter.
7. **Command Reception and Execution:**
   The RF receiver on the vehicle passes the command to the ESP8266, which drives the motor driver to perform the desired movement.
8. **Obstacle Detection:**
   The ultrasonic sensor continuously scans the environment.
   a. If an obstacle is detected, the system overrides movement commands and issues a Stop action.
   b. If no obstacle is detected, the vehicle continues moving according to the user's brain/eye input.
9. **Vehicle Motion:**
   Based on motor driver output, the vehicle executes forward, backward, or turning movements.

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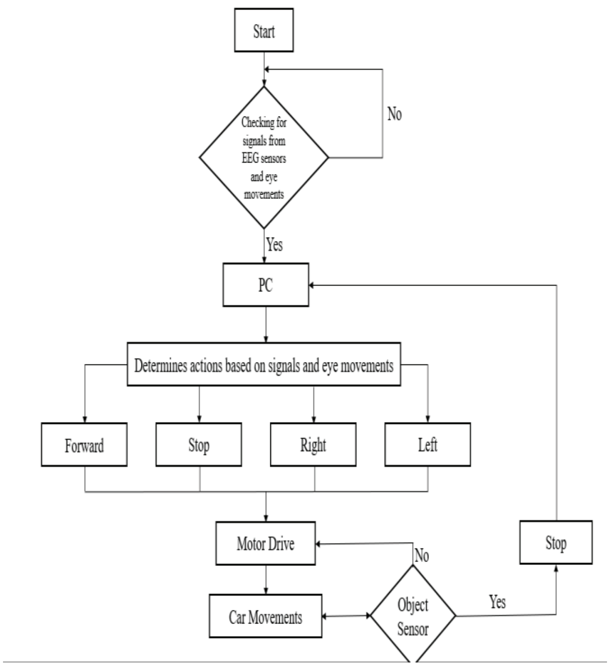


Fig.2. Flow Chart

D. Cir it Diagram

The circuit diagram integrates the user-side transmitter module and the vehicle-side receiver module to enable seamless brain-wave–based control of the electric vehicle. On the transmitter side, the EEG sensor captures brain-wave activity and sends the raw signals to a signal-conditioning stage, which filters noise and stabilizes the waveform. These processed signals, along with inputs from the eye-movement detection module consisting of X-, Y-, and Z-axis switches, are fed into an ESP8266 microcontroller. The microcontroller analyzes the combined EEG and eye-movement data and converts them into control commands. These commands are transmitted wirelessly through an RF transmitter.

On the vehicle side, an RF receiver obtains the transmitted signals and forwards them to another ESP8266 module responsible for executing motion commands. The ESP8266 controls the L298N motor driver, which regulates the speed and direction of the DC motors. The system is powered by solar cells that charge a battery through a charge controller, ensuring continuous energy supply for both the motors and electronic components. Additionally, an obstacle-detection sensor is integrated into the circuit to ensure safe operation. When an obstacle is detected, the sensor signals the ESP8266 to override user commands and immediately stop the vehicle. This integrated circuit ensures reliable, wireless, and safe navigation.

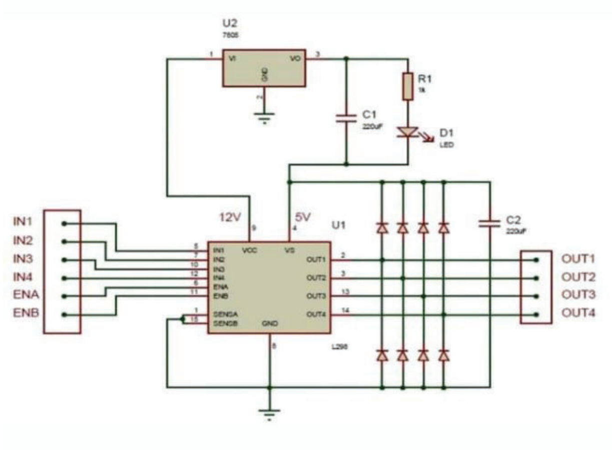
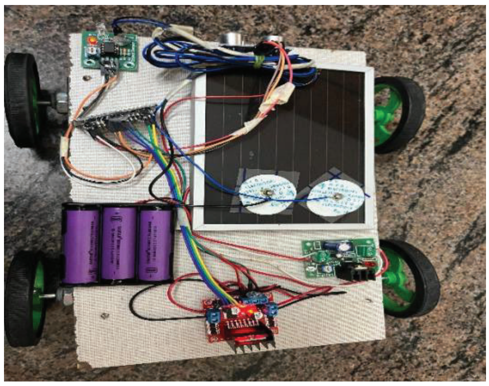


Fig.3. Circuit Connection

E. System Setup

The system setup involves assembling the user-side control unit and the vehicle-side execution unit to enable smooth brain–computer–based navigation. The user module, consisting of the EEG sensor, eye-movement detection circuit, and ESP8266 microcontroller, is arranged so that the sensors maintain stable contact with the user while allowing comfortable operation. The EEG headset is positioned on the user's forehead to ensure accurate acquisition of neural signals, and the eye-movement sensors are aligned to capture horizontal and vertical eye gestures effectively. These components are connected to the ESP8266, which is powered using a compact rechargeable battery to allow unrestricted mobility.

The vehicle-side module includes the RF receiver, secondary ESP8266 controller, motor driver, DC motors, obstacle-detection sensor, and solar-powered battery system. All electronic components are securely mounted on the chassis,



with the solar panel positioned at the top for maximum light exposure. The motor driver is connected to the motors and regulated through the ESP8266, while the ultrasonic sensor is placed at the front of the vehicle to detect obstacles. Power regulation circuits ensure that both the microcontroller and motors receive stable voltage. After assembly, the system is calibrated to synchronize EEG signals, eye-movement cues, and motor responses, resulting in a fully functional brain-controlled electric vehicle.

Fig.4. Hardware Setup

F. Advantages of the Proposed System

The proposed system offers hands-free vehicle control, enabling individuals with motor impairments to navigate independently using brain signals and eye movements. The hybrid EEG–eye interface increases command accuracy and responsiveness compared to EEG-only systems. Solar-powered operation ensures energy efficiency, sustainability, and reduced reliance on external charging. Integrated obstacle detection enhances safety by automatically stopping the vehicle when an object is detected. Wireless communication provides flexible, cable-free control, while the modular design allows easy expansion with additional sensors or advanced algorithms. Overall, the system delivers a reliable, eco-friendly, and user-centric mobility solution.

IV. RESULT AND DISCUSSION

Fig.4. EEG Signals

The displayed brainwave monitoring dashboard shows real-time EEG activity streamed from a connected headset, indicated by the green status icon. The central "Stream" graph plots brainwave intensity between 0 and 1000 units, reflecting fluctuations in neural activity such as focus, relaxation, or eye-related artifacts. The waveform updates continuously in "Live" mode, confirming active signal reception. Time-range options like 1H, 1D, and 1W allow historical data review. This interface is useful for BCI applications, as it verifies sensor connectivity, signal quality, and the presence of identifiable neural patterns required for controlling the proposed brain-controlled vehicle. The central element of the screen is a line graph titled "Stream," which represents variations in brainwave intensity or signal values over time. The vertical axis (Y-axis) ranges from 0 to 1000 units, indicating the amplitude or strength of the recorded EEG signals. The plotted line fluctuates with multiple peaks and dips, showing dynamic brain activity. Higher peaks indicate increased mental engagement, focus, or certain cognitive/emotional states, while lower points represent calmness, reduced activity, or transitions in thought patterns.

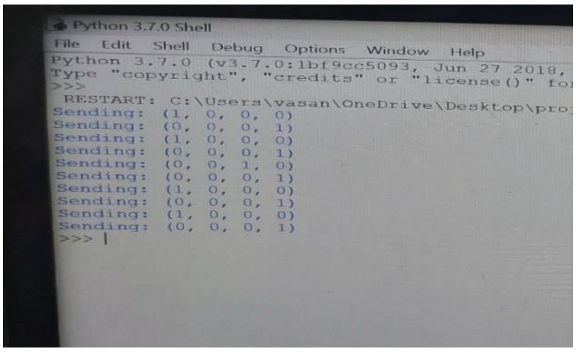


Fig.5. Python 3.7.0 IDLE Shell Readings

The Python 3.7.0 IDLE Shell displays a program that continuously prints "Sending:" followed by four binary values, each representing a motor command for the brain-controlled vehicle. These binary tuples correspond to specific actions such as forward, backward, left, or right. The script generates these commands based on detected EEG patterns, eye blinks, or neural events, and transmits them to the hardware through serial or Bluetooth communication. The alternating outputs indicate that the system is actively recognizing different neural triggers. This real-time printout is valuable for debugging, as it confirms accurate signal interpretation and proper mapping of brainwave events to movement commands.

V. CONCLUSION

The developed brain-wave–controlled and solar-powered electric vehicle demonstrates an effective hands-free mobility solution designed specifically for individuals with physical disabilities. By integrating EEG-based brainwave detection with eye-movement recognition, the system provides a hybrid control mechanism that significantly enhances accuracy, responsiveness, and reliability compared to conventional single-input BCI systems. This dual-input method minimizes misclassification, improves user adaptability, and enables smoother navigation. Safety is ensured through the inclusion of an obstacle-detection module, which autonomously halts the vehicle whenever a potential collision is detected, thereby enhancing user protection during operation. In addition to its functional advantages, the system incorporates a solar-powered energy architecture, eliminating reliance on external charging sources and supporting long-term, eco-friendly operation. This sustainable design not only reduces energy consumption but also makes the vehicle more practical for outdoor usage and extended mobility sessions. The combination of renewable energy, intelligent signal processing, and real-time wireless control creates a robust platform for future advancements. Overall, the project represents a significant step toward intelligent assistive mobility devices that merge neuroscience, embedded systems, and green energy. The successful integration of these technologies highlights the potential for more advanced, autonomous, and accessible mobility solutions for individuals with severe motor impairments.

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VI. UTURE SCOPE

The proposed brain-wave–controlled and solar-powered electric vehicle offers a strong foundation for future enhancements in assistive mobility. Upcoming versions of the system can incorporate advanced machine-learning algorithms to improve EEG signal classification, enabling recognition of a wider range of mental commands with higher accuracy. Integrating additional physiological sensors such as heart rate, muscle activity, or eye-tracking cameras can further enhance control reliability and user safety. Communication can be upgraded using long-range wireless technologies like LoRa, Wi-Fi 6, or 5G to support remote monitoring and cloud-based data analytics. Autonomous navigation features, including AI-based path planning and environment mapping, may also be implemented to reduce user cognitive load. Improvements in solar efficiency and energy-harvesting techniques can extend operational time and reduce battery dependence. A modular hardware design could allow customization for wheelchairs, personal mobility devices, or robotic platforms, broadening the system's real-world applicability.

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