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Restoring Independence: Development of an EEG-Controlled Prosthetic Arm for Activities of Daily Living

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ABSTRACT: The loss of upper-limb functionality greatly affects a person's independence in performing daily activities. This project presents a non-invasive EEG-based brain–machine interface system for controlling a prosthetic arm. Brain signals are acquired using a Bio-Amplifier EEG sensor and digitized through an analog-to-digital converter. The processed signals are handled by an ESP32 WROOM microcontroller for real-time analysis. Variations in Mu and Beta frequency bands generated during motor imagery are extracted using Fast Fourier Transform. These features are translated into control commands for operating the prosthetic arm. A servo driver controls the motors of the robotic arm structure to perform wrist and gripper movements. The system is powered by a Li-ion battery pack for portability and continuous operation. An OLED display provides a simple user interface for monitoring system status. The proposed system demonstrates an affordable and expandable neuro prosthetic solution. This technology aims to restore partial independence for individuals with upper-limb disabilities. The prosthetic arm is capable of performing essential activities such as grasping and releasing objects. User training requirements are minimal due to simplified control strategies. The system architecture supports future upgrades, including machine learning integration for improved performance. Experimental validation confirms the feasibility of using EEG signals for assistive prosthetic control in real-world applications.

KEYWORDS: EEG Sensor, Bio-amplifier, ESP32 WROOM, Servo Motor Prosthetic Arm

I. INTRODUCTION

Limb loss is a serious physical disability that can occur due to traumatic accidents, severe injuries, congenital conditions, infections, cancer, or chronic diseases such as diabetes and vascular disorders, and it significantly affects an individual's ability to live independently. The loss of an upper limb greatly limits a person's capacity to perform everyday activities such as eating, dressing, writing, holding objects, and maintaining personal hygiene. These basic tasks become extremely difficult, often forcing individuals to depend on caregivers or family members for daily support. This dependency can reduce confidence and create a sense of helplessness in affected individuals. In addition to physical challenges, limb loss also leads to psychological and emotional issues such as reduced self-esteem, social isolation, stress, and difficulty in adapting to a new lifestyle. Many individuals find it hard to return to work or actively participate in social activities, which further affects their overall quality of life and well-being. To overcome these challenges, there is a growing need for advanced assistive and rehabilitation technologies that can restore independence. In this context, the development of an EEG-controlled prosthetic arm offers a promising solution. By using electroencephalography signals, the system captures brain activity and translates it into control commands for the prosthetic arm. This allows users to control the arm using their thoughts, enabling more natural and intuitive movement. The proposed project focuses on restoring independence by designing a prosthetic arm capable of performing activities of daily living with improved accuracy and responsiveness. It helps users regain the ability to perform essential tasks such as gripping, lifting, and handling objects. The integration of intelligent control systems enhances functionality and user adaptability. This technology not only improves physical capabilities but also boosts confidence and social interaction. The use of motor imagery signals, particularly in the Mu and Beta frequency bands, allows users to generate control commands by simply imagining movements. This makes EEG-based prosthetic systems highly beneficial for individuals with severe motor impairments. Furthermore, the integration of microcontrollers such as ESP32 enables real-time processing and wireless capabilities, enhancing system efficiency.

II. METHODOLOGY

The proposed system consists of multiple stages, including signal acquisition, preprocessing, feature extraction, classification, and actuation. EEG signals are acquired using non-invasive electrodes placed on specific regions of the scalp associated with motor activity. These signals are typically weak and susceptible to noise, requiring amplification and filtering to improve signal quality. Preprocessing techniques such as band-pass filtering and artifact removal are applied to eliminate interference from eye blinks, muscle movements, and environmental noise. Feature extraction methods, including Fast Fourier Transform (FFT) and wavelet transforms, are used to identify relevant patterns in the EEG signals. The extracted features are then fed into machine learning classifiers such as Support Vector Machines (SVM) or Artificial Neural Networks (ANN) to distinguish between different user intentions. Once classified, the output signals are mapped to corresponding movements of the prosthetic arm. An embedded microcontroller, such as ESP32, is used to process the classified signals and generate control commands. These commands are transmitted to servo motors that drive the movement of the prosthetic arm and fingers. The system is designed to operate in real time, ensuring minimal delay between user intention and device response. Feedback mechanisms, such as visual or sensory cues, are incorporated to improve user control and system accuracy. The overall design emphasizes efficiency, reliability, and ease of integration.

III. LITERATURE SURVEY

Title: Cognitive Arm — Enabling Real-Time EEG-Controlled Prosthetic Arm Using Embodied Machine Learning
Author: Abdul Basit, Maha Nawaz, Saim Rehman, Muhammad Shafique
Year:2025
This research presents an advanced real-time embedded prosthetic arm controlled using EEG signals integrated with deep learning techniques. The system focuses on interpreting brain signals accurately to enable intuitive prosthetic control. It achieves approximately 90% accuracy in recognizing user intentions, which is a significant improvement in EEG-based systems. The prosthetic arm supports multiple real-life tasks such as handshakes and picking up objects like cups. A key feature of this system is its real-time processing capability, which allows immediate response without external computing dependency. The embedded design ensures portability and practical usability in daily life. Additionally, the system includes a voice control mode, offering flexibility and multimodal interaction. This combination of EEG-based control and voice commands enhances user convenience. The research emphasizes embodied machine learning, where processing occurs within the device itself. This reduces latency and increases efficiency. The system demonstrates improved adaptability to user behavior. It also highlights advancements in neuro prosthetics for restoring independence. The integration of AI with brain-computer interfaces makes the system more reliable. The study contributes to developing intelligent assistive devices. It also addresses usability challenges faced by amputees. Overall, the research represents a step forward in creating natural and responsive prosthetic systems.

Title: BIONIX: A Wireless, Low-Cost Prosthetic Arm with Dual-Signal EEG and EMG Control
Author: Pranesh Sathish Kumar
Year: 2025
This research introduces BIONIX, a wireless prosthetic arm system that integrates both EEG and EMG signals for enhanced control. The system is designed to be cost-effective, with an approximate cost of $240, making it accessible to a wider population. By combining brain and muscle signals, the prosthetic achieves multi-degree-of-freedom movement, improving flexibility and precision. The dual-signal approach enhances responsiveness compared to traditional single-signal systems. EEG signals capture user intent, while EMG signals provide muscle activity feedback, resulting in more accurate motion control. The wireless design improves portability and user convenience, eliminating the need for complex wired setups. The system supports daily activities and enhances independence for individuals with limb loss. The research emphasizes affordability without compromising performance. Advanced signal processing techniques are used to reduce noise and improve signal clarity. The integration of multiple control inputs allows smoother transitions between movements. The study highlights the importance of user adaptability in prosthetic design. It demonstrates that combining different biological signals can significantly improve system efficiency. The wireless feature ensures ease of use in real-world environments. The research also focuses on improving battery efficiency for

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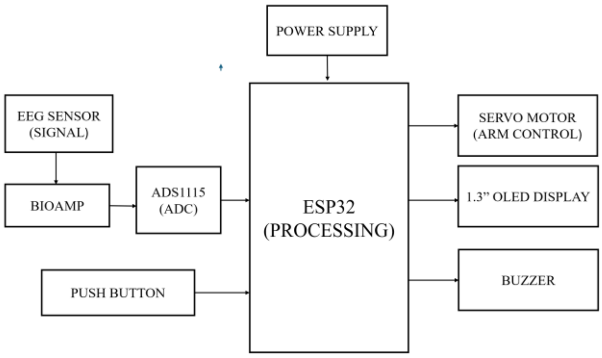
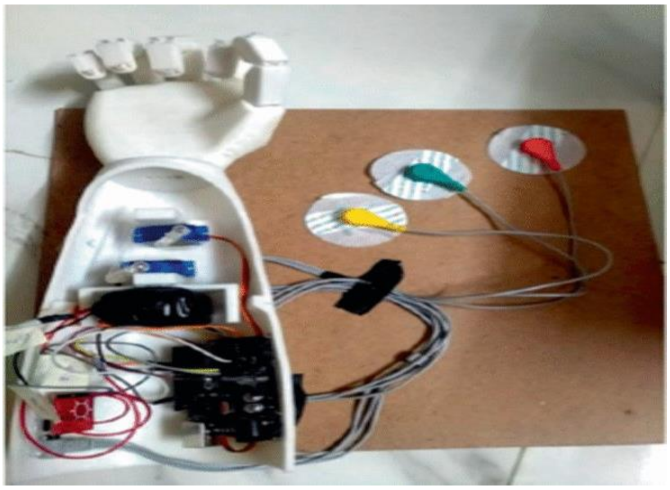
prolonged usage. Overall, BIONIX represents a practical and scalable solution in neuro prosthetic development. It contributes to making advanced prosthetic technology more accessible and effective

IV. BLOCK DIAGRAM



V.RESEULT AND DISCUSSION

The experimental evaluation of the proposed EEG-controlled prosthetic arm demonstrates promising results in terms of accuracy, responsiveness, and usability. The system was tested with multiple users performing different motor imagery tasks, such as imagining hand movements. The machine learning classifiers achieved satisfactory accuracy in distinguishing between different commands, enabling reliable control of the prosthetic arm. The response time of the system was found to be suitable for real-time applications, allowing smooth and continuous movement. Users were able to perform basic activities of daily living, such as grasping objects, lifting items, and releasing them, with reasonable ease. However, the performance of the system was affected by factors such as signal noise, electrode placement, and user training. Variability in EEG signals between different users also posed challenges in achieving consistent performance. Adaptive algorithms and training sessions were found to improve accuracy over time. The use of lightweight and low-cost components makes the system practical for real-world deployment. Compared to traditional prosthetic systems, the EEG-based approach offers a more intuitive and natural mode of control. The results indicate that the proposed system is a viable solution for assistive applications, although further improvements are required to enhance robustness and scalability.



VI.CONCLUSION

Development of an EEG-controlled prosthetic arm designed to restore independence for individuals with upper limb disabilities. The system successfully integrates EEG signal acquisition, signal processing, machine learning, and robotic control to achieve real-time operation. The use of non-invasive EEG technology ensures safety and ease of use, while

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machine learning algorithms enhance the accuracy of signal interpretation. The experimental results demonstrate that the proposed system can effectively translate user intentions into prosthetic movements, enabling the performance of basic daily activities. The design emphasizes affordability, portability, and user comfort, making it suitable for widespread adoption. Despite its advantages, the system faces challenges such as signal variability, noise interference, and the need for user training. Future work will focus on improving signal processing techniques, developing more advanced classification algorithms, and integrating sensory feedback mechanisms for better user interaction. Additionally, the incorporation of IoT and cloud-based technologies can enable remote monitoring and data analysis. The proposed system represents a significant step toward the development of intelligent assistive devices and highlights the potential of brain-computer interfaces in rehabilitation engineering. Ultimately, this work contributes to enhancing the quality of life and independence of individuals with physical disabilities.

VII.FUTURE WORK

Future advancements in EEG-controlled prosthetic arms aim to enhance user independence and functionality. Key areas of development include:

1. **Real-Time Signal Processing and Machine Learning**: Implementing deep learning models, such as EEG Net, enables accurate decoding of brain signals for prosthetic control. Fine-tuning these models enhances real-time performance, allowing for precise control of individual finger movements.
2. **Integration of Augmented Reality for Feedback**: Augmented reality (AR) interfaces provide visual feedback, improving user interaction with prosthetic devices. Combining AR with EEG-based control systems enhances stability and accuracy during tasks like grasping and manipulation.
3. **Development of Affordable Prosthetic Solutions**: Projects like Mind Arm focus on creating low-cost, non-invasive neuro-driven prosthetic arms. Utilizing open-source hardware and deep neural networks, these systems offer accessible solutions for users requiring prosthetic assistance.
4. **Incorporation of Sensory Feedback Mechanisms**: Integrating sensory feedback, such as electroactive stimulation, into prosthetic devices restores the sense of touch. This enhancement allows users to perceive pressure and texture, improving the functionality and comfort of prosthetic limbs.
5. **Voice Command Integration for Enhanced Control**: Combining EEG-based control with voice commands enables seamless operation of prosthetic arms. Systems like Cognitive Arm demonstrate the feasibility of real-time control with integrated voice commands, enhancing user experience and task execution

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