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Impulse Flexomind

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Abstract: Impulse Flexomind revolves around a multi-model approach to guide the robotic arm that is controlled by brain. The human brain consists of hundreds of millions of neurons. The utilization of an Electroencephalogram (EEG) based Brain Computer Interface (BCI) prosthetic arm offers a promising non-invasive approach to support individuals with significant disabilities in their daily lives. This innovative technology has the capability to empower users by facilitating voluntary movements of the prosthetic arm, enhancing their ability to engage in various activities with greater independence and control. The EEG signals from the brain are captured in Brain BioAmp headband and are processed by a microcontroller (Arduino UNO) to control servo motors and move the Prosthetic hand accordingly. It also involves a glove equipped with flex sensors that mimics the gestures. The technique involves the control of the arm motion with the aid of flex sensors. The voice control system is developed in order to control prosthetic arm by giving voice signals via Bluetooth. All operations can be monitored by a user interface with the support of a microcontroller. Individuals who have undergone amputation below the elbow can find significant advantages in utilizing this prosthetic arm. This prosthetic arm empowers physically disabled individuals to regain their independence and reduces their reliance on others to accomplish their daily tasks. This model would be highly useful in practice, especially, for arm amputees and paralyzed patients.
Keywords: Brain-Computer Interface, Brain BioAmp headband, Robotic arm, Human-Computer Interaction.

INTRODUCTION

The scope of brain-controlled prosthetic hands is extensive and continually advancing, offering transformative potential across the domains of medicine, neuroscience, robotics, and human augmentation. These next-generation prosthetic systems employ Brain–Computer Interfaces (BCIs) to interpret electroencephalographic (EEG) or other neural signals generated by the user's brain and translate them into real-time motor commands for the artificial limb. Through this direct neural control, users such as amputees, individuals with spinal cord injuries, or patients affected by neuromuscular disorders can regain voluntary and precise movement of the prosthetic hand using cognitive intent alone. This capability marks a paradigm shift in assistive technology, moving from mechanical and myoelectric control methods toward neuroadaptive and thought-driven interaction.

1. Background of Prosthetics and EEG Systems

Prosthetic technology has undergone remarkable evolution over the past few decades, transitioning from simple mechanical attachments to sophisticated bio-integrated systems. Traditional prosthetic limbs primarily rely on mechanical joints and manual control, providing only limited functionality and dexterity. The introduction of myoelectric prosthetics, which utilize electromyographic (EMG) signals from residual muscles, marked a significant advancement by allowing more natural limb movement. However, these systems still depend heavily on muscular input and lack seamless integration with the user's neural intentions. Recent advancements in neuro engineering and Brain–Computer Interface (BCI) research have opened the door to a new generation of brain-controlled prosthetic hands.

Among various neural recording techniques, Electroencephalography (EEG) has emerged as a promising non-invasive approach for capturing brain activity. EEG measures voltage fluctuations resulting from ionic current flows within the neurons of the brain, thereby enabling real-time monitoring of motor imagery and cognitive intent. When integrated with intelligent signal processing and machine learning algorithms, EEG-based BCIs can decode user intentions and translate them into precise prosthetic control signals, bridging the communication gap between the brain and the artificial limb.

2. Limitations of Existing Prosthetic Control Methods

Despite notable progress, conventional prosthetic control technologies continue to face several challenges that limit their performance, adaptability, and user acceptance.

- Myoelectric systems, though widely used, rely on surface muscle activity and often suffer from signal interference, low precision, and fatigue-related inconsistencies. They are also unable to serve patients with high-level amputations or neuromuscular impairments where residual muscle signals are weak or absent.
- Mechanically controlled prosthetics are constrained by limited motion range and lack of intuitive control, demanding substantial cognitive effort from users.
- Invasive BCI systems, while offering high signal accuracy, require surgical implantation of electrodes, posing ethical, medical, and financial concerns.

These limitations collectively underscore the need for a non-invasive, reliable, and intelligent control mechanism capable of providing real-time, naturalistic movement with minimal user strain. Furthermore, existing systems rarely provide bidirectional sensory feedback—a critical factor in restoring the sense of touch and improving motor precision. Without sensory feedback, users often struggle with grasping force regulation and proprioceptive awareness, reducing both performance efficiency and user satisfaction. Hence, there exists a pressing need for prosthetic systems that integrate EEG-based control with adaptive sensory feedback and AI-driven decision mechanisms.

3. Objective and Motivation Behind IMPULSE FLEXOMIND

The proposed system, IMPULSE FLEXOMIND, aims to overcome the aforementioned limitations by developing an EEG-based brain-controlled prosthetic arm that translates neural activity directly into motor actions. The core objective is to enable thought-driven movement of a prosthetic limb, thereby restoring autonomy and functional independence to individuals with upper-limb disabilities.

The motivation behind IMPULSE FLEXOMIND lies in harnessing non-invasive neural decoding and intelligent control architectures to create a system that is:

- Adaptive – capable of learning and refining control patterns from user brain activity over time;
- Responsive – translating EEG signals into smooth, real-time movement commands;
- Affordable and Accessible – reducing reliance on costly invasive procedures; and
- Human-Centric – designed to integrate seamlessly with natural cognitive and motor processes.

By incorporating EEG signal processing, machine learning-based intent classification, and robotic actuation, IMPULSE FLEXOMIND aims to establish a closed-loop BCI prosthetic framework that not only executes motor commands but can also be extended to include sensory feedback mechanisms in future iterations. This integration will help users perceive tactile responses, enabling a more natural and immersive experience.

4. Broader Implications and Future Scope

The successful implementation of brain-controlled prosthetic systems such as IMPULSE FLEXOMIND represents a significant leap in assistive and rehabilitative technology. Beyond medical rehabilitation, such systems contribute to broader research areas including neural decoding, neuroplasticity, and human–machine symbiosis. As advancements in EEG acquisition, AI-based signal interpretation, and neurofeedback continue, the future of prosthetic technology promises more intuitive, intelligent, and personalized prosthetic hands, ultimately redefining the boundaries between biological intelligence and artificial augmentation.

PROPOSED SYSTEM

The proposed system, IMPULSE FLEXOMIND, is a brain-controlled prosthetic hand designed to translate neural activity into real-time prosthetic motion using EEG-based Brain–Computer Interface (BCI) technology. The system architecture, illustrated in Fig. X, is organized into six functional layers: EEG Signal Acquisition, Signal Processing and Feature Extraction, Machine Learning and Classification, Communication and Microcontroller Processing, Prosthetic Hand Actuation, and User Feedback & Optimization. Each stage is integral to achieving accurate, responsive, and adaptive prosthetic control.

4.1 EEG Signal Acquisition Layer

This layer forms the foundation of the system, where Electroencephalography (EEG) sensors are employed to non-invasively capture brain signals corresponding to motor imagery or intent. When a user imagines a hand movement—such as grasping, opening, or rotating—the EEG headset records voltage fluctuations generated by neural activity in the motor cortex. The system employs multi-channel EEG sensors positioned according to the international 10–20 electrode placement system to ensure optimal spatial coverage and signal fidelity. These signals are then transmitted to the processing unit for further analysis.

4.2 Signal Processing and Feature Extraction

The raw EEG signals acquired are often contaminated by noise, eye-blink artifacts, and environmental interference. Therefore, this stage performs signal preprocessing, including bandpass filtering, artifact removal, and normalization to isolate the relevant frequency bands (typically α, β, and μ rhythms).

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Feature extraction is then performed using statistical and spectral methods such as Fast Fourier Transform (FFT), Common Spatial Patterns (CSP), or Wavelet Transform to derive meaningful features that represent the user's cognitive state. These features serve as inputs to the machine learning classifier for intent recognition.

4.3 Machine Learning and Classification

At this stage, extracted EEG features are analyzed using machine learning algorithms that classify user intentions into specific control commands. Supervised learning models such as Support Vector Machines (SVM), Convolutional Neural Networks (CNN), or Linear Discriminant Analysis (LDA) are commonly used to distinguish between different mental tasks, such as "open hand," "close hand," or "rest."

The classifier outputs are continuously refined through adaptive training, allowing the system to improve accuracy and responsiveness over time, accommodating individual user differences in neural patterns.

4.4 Communication and Microcontroller Processing

Once classified, the control signals are transmitted to the microcontroller via a wireless communication interface such as Bluetooth or Wi-Fi. The microcontroller—typically an Arduino, ESP32, or Raspberry Pi—interprets these digital commands and generates the appropriate Pulse Width Modulation (PWM) signals to drive the prosthetic actuators. This layer serves as the bridge between the computational module and the physical hand.

4.5 Prosthetic Hand Actuation

The prosthetic hand consists of servo or DC motors arranged to replicate human finger and wrist motion. Upon receiving control signals, the actuators execute corresponding mechanical movements, allowing the artificial hand to perform actions such as gripping, lifting, or rotating objects. The mechanical design emphasizes lightweight construction, ergonomic fitting, and smooth joint articulation to ensure natural and comfortable use.

4.6 User Feedback and Optimization

The final stage integrates user feedback mechanisms to enhance adaptability and control precision. Feedback can be visual, haptic, or auditory, providing the user with real-time information about the prosthetic's position and grip strength. Additionally, performance metrics from continuous use are analyzed to optimize classifier performance and signal calibration, forming a closed-loop adaptive system. Over time, the prosthetic learns and adjusts to the user's neural activity, increasing both comfort and intuitiveness.

4.7 System Advantages

- Non-invasive control using EEG eliminates the need for surgical implantation.
- Adaptive machine learning models allow continuous system improvement.
- Low-cost and modular design enhances accessibility for rehabilitation centers.
- Bidirectional interaction enables a more natural, human-like prosthetic experience.

LITERATURE REVIEW

Advancements in brain–computer interface (BCI) technology have significantly enhanced the efficiency of neural signal processing, improved control accuracy in prosthetic movements, and increased the overall intelligence and adaptability of prosthetic systems.

[1] Md.S.Ahsan and K.M. asan (2020), in their IEEE ICECIT paper "Development of Noninvasive EEG Brain Sensor Actuated Motorized Prosthetic Arm to Support Disabled People," introduced a non-invasive EEG-based BCI system designed to operate a motorized prosthetic arm using brain activity. Their approach classified EEG motor imagery signals and translated them into control commands for real-time hand movement. The study demonstrated effective thought-driven prosthetic control, highlighting its potential as an affordable, accessible, and reliable neuroprosthetic solution for individuals with upper-limb impairments and rehabilitation needs.

[2] S.Kumar et al. (2024), in their IEEE Access paper, proposed a hybrid BCI system for real-time prosthetic arm control. The model combined EEG-based neural decoding, machine learning, and sensor fusion to improve precision and speed, demonstrating high accuracy, adaptability, and stability for advanced prosthetic applications.

[3] A.Sharma et al. (2025), in their IEEE Transactions on Biomedical Engineering paper titled "Advances in Brain–Computer Interface Based Prosthetic Control Using Deep Learning Models," presented a BCI framework that employs deep learning algorithms for enhanced prosthetic control. Their approach improved EEG signal decoding accuracy and movement prediction, demonstrating faster, more reliable, and adaptive brain-controlled prosthetic performance.

[4] P.Avari and B.K.Patle (2022), in their IJRAR paper "Review on Biomechatronic Hand," presented an overview of biomechatronic hand designs integrating mechanical, electronic, and biological systems. The review highlighted advancements in sensor technology, control mechanisms, and material design, emphasizing improved dexterity, responsiveness, and user comfort in modern prosthetic hands.

[5] C.Gentile and E.Gruppioni (2023), in their Prosthesis paper "A Perspective on Prosthetic Hands Control: From the Brain to the Hand," discussed the evolution of prosthetic hand control systems from neural signal acquisition to actuation. The study emphasized the integration of brain–computer interfaces, sensory feedback, and adaptive control, outlining future directions for achieving natural, intuitive, and seamless brain-to-hand communication in prosthetic design.

[6] C.Gentile, F.Cordella, and L.Zollo (2022), in their Sensors paper "Hierarchical Human-Inspired Control Strategies for Prosthetic Hands," proposed a multi-level control approach modeled on human motor control principles. Their framework integrated sensory feedback, adaptive motion planning, and hierarchical control layers, achieving more natural, coordinated, and efficient hand movements in prosthetic systems.

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[7] María F. Carballo Turcios and Manuel A. Gamero-V. (2024), in their LACCEI Conference paper "Development of a Hand Prosthesis Controlled by EEG Signals Using Arduino and Mindflex Technology," developed a low-cost EEG-controlled prosthetic hand using Arduino and Mindflex hardware. Their system successfully translated EEG brain signals into hand movements, demonstrating a simple, accessible, and effective approach to brain-controlled prosthetic design.

[8] Ning Lan, Manzhao Hao, Chuanxin M. Niu et al. (2021), in their Research paper "Next-Generation Prosthetic Hand: From Biomimetic to Biorealistic," explored the transition from biomimetic to biorealistic prosthetic designs. Their study focused on integrating neural interfaces, sensory feedback, and adaptive control to replicate natural hand movement and perception, paving the way for next-generation prosthetics that closely emulate human functionality.

[9] Julia Żaba and Szczepan Paszkiel (2023), in their Journal of Automation, Mobile Robotics and Intelligent Systems paper "Concept of Using the Brain–Computer Interface to Control Hand Prosthesis," proposed a BCI-based prosthetic hand control model using EEG signal analysis. Their concept focused on translating brain activity into precise motor commands, demonstrating the potential of EEG-driven prosthetic control for improving mobility and independence in users.

[10] Pritam Avari and B. K. Patle (2021), in their IJRAR paper "Review on Biomechatronic Hand," presented an extensive review of biomechatronic hand technologies, emphasizing the integration of mechanical, electronic, and biological systems. The study discussed advancements in sensors, actuators, and control strategies, highlighting progress toward more efficient, responsive, and human-like prosthetic hand designs.

FIGURES

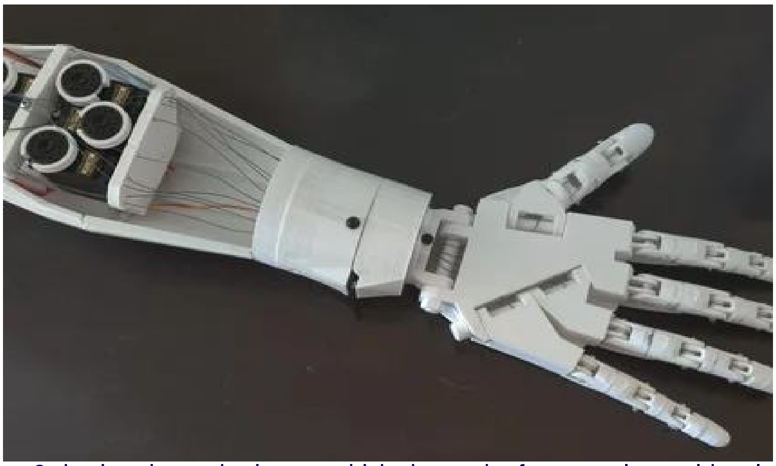

Fig 1. depicts a 3-d printed prosthetic arm which shows the forearm along with palm and fingers (Each separated tendons).

Source: Indestructables (hand design)

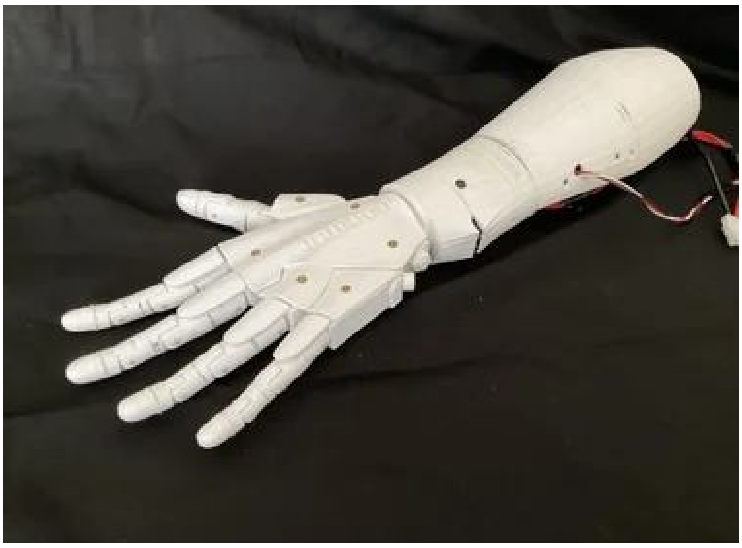

Fig 2. depicts a 3-d printed prosthetic arm which shows the rear forearm along with wrist joints, palm and fingers(each with respective protectors).

Source: Indestructables (hand design)

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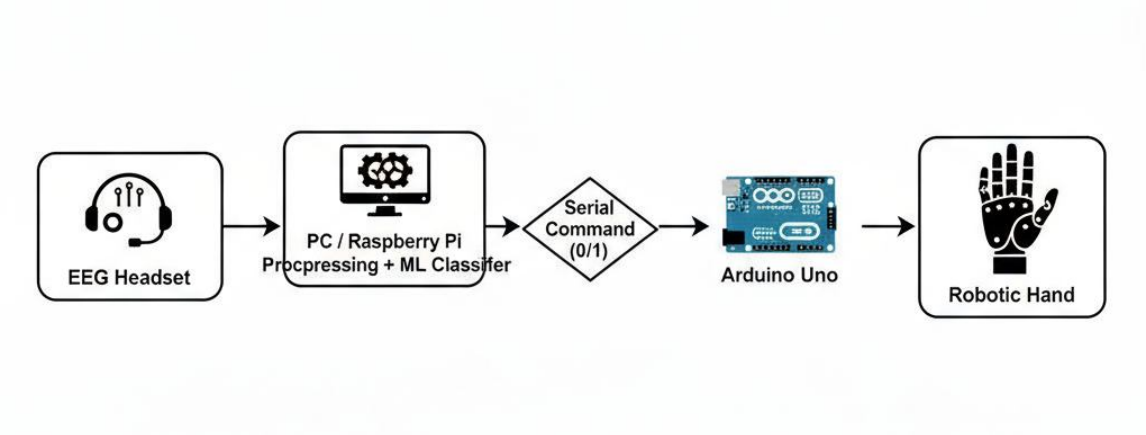
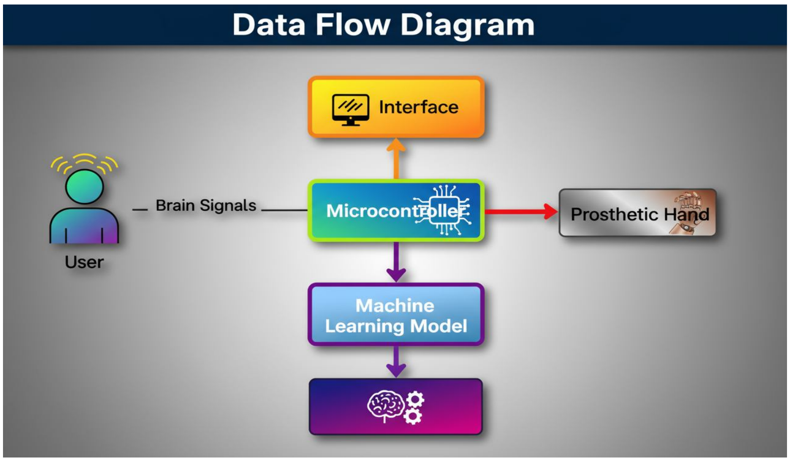
METHODOLOGY



Source: Comet

Fig 3. depicts the workflow starting from brain signals acquisition till the movement of the arm.



Source: Comet

Fig 4. depicts the dataflow starting from user till the movement of the arm.

METHODOLOGY LAYERS AND DESCRIPTION

1. EEG Headset Layer
2. Function: Captures the user's brainwave signals (EEG data).
3. Explanation: This is the sensory interface, converting neural signals into digital data for further processing.
4. PC/Raspberry Pi Layer (Preprocessing + ML Classifier)
5. Function: Processes raw EEG signals, applies machine learning algorithms to classify intended actions.
6. Explanation: Acts as the decision-making and signal processing center. Preprocessing filters and cleans the data, while the ML classifier interprets whether the user intends to move the prosthetic hand.
7. Serial Command Layer (0/1)
8. Function: Communicates classification results to the microcontroller using simple digital signals (e.g., 0 or 1).
9. Explanation: Serves as the bridge, translating high-level decisions into actionable commands that control hardware.
10. Arduino Uno Layer
11. Function: Receives commands via serial communication, acts as the main hardware control unit.
12. Explanation: This microcontroller interfaces between the classifier and actuators, executing instructions for movement.
13. Servo Motors Layer
14. Function: Actuate/mechanically move the prosthetic hand based on Arduino instructions.
15. Explanation: Physical motors that respond to electrical input, producing desired movements in the prosthetic.
16. Robotic Hand Layer
17. Function: The final actuator performing movements intended by user's neural activity.

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ABOUT THE AUTHORS

The authors are undergraduate researchers keen on biomedical engineering, AI, and human–machine interaction. Their IMPULSE FLEXOMIND project shows how EEG-based BCI and machine learning can make affordable, smart prosthetic solutions for people with disabilities. They focus on neuroprosthetics, IoT healthcare, and adaptive control systems for future assistive devices.

Anush Richard is a Graduating Student at Vemana Institute of Technology, Bengaluru, specialising in Artificial Intelligence and Machine Learning. He is passionate about innovative technologies in Robotics and machine Learning and has participated in research and technical events to advance his interests.

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