

# Manohastha: A BCI-Driven Extendable Robotic Arm

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<https://doi.org/10.55041/ijst.v2i5.366>

**Cite this Article:** Reddy, D. L., Kammar, U., Marathi, A. V. & R, D. C. (2026). Manohastha: A BCI-Driven Extendable Robotic Arm. International Journal of Science, Strategic Management and Technology, 02(05). <https://doi.org/10.55041/ijst.v2i5.366>

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## Abstract—

Brain-Computer Interface (BCI) technology has emerged as a transformative approach for enabling direct communication between human cognition and robotic systems, particularly in rehabilitation and hazardous-environment applications. This paper presents *ManoHashta*, a low cost, non-invasive BCI-driven extendable robotic arm designed to convert neural intent into mechanical actuation using Electroencephalography (EEG) and Electrooculography (EOG) signals. The proposed system integrates a BioAmp EXG Pill for bio-signal acquisition, an Arduino Nano for signal conditioning and analog to digital conversion, and an ESP32 microcontroller for wireless communication and robotic control. The robotic manipulator operates based on voluntary eye blinks and sustained attention levels, allowing users to perform reach-and-grab operations

without physical interaction. A hybrid processing architecture was implemented to reduce latency and improve operational reliability. Experimental evaluation demonstrated accurate detection of intentional blink patterns and stable attention-based control with an overall response latency of approximately 125 ms, ensuring near real-time performance. The complete system was developed with a total hardware cost below ₹10,000, making advanced neuro-robotic technology more accessible for educational, assistive, and industrial safety applications. The results confirm that *ManoHashta* provides a reliable and affordable framework for practical BCI-enabled robotic manipulation.

**Keywords—** Brain-Computer Interface (BCI); EEG Signal Processing; Robotic Arm; ESP32; Neuro-Robotics; Human-Machine Interaction

## I. INTRODUCTION

The rapid advancement of intelligent automation and human-machine interaction technologies has significantly transformed the fields of robotics, healthcare, and industrial safety. Among these developments, Brain-Computer Interface (BCI) systems have emerged as a promising technology that enables direct communication between the human brain and external electronic devices without requiring physical movement [1]. By interpreting neural activity generated within the brain, BCI systems provide an alternative pathway for controlling machines, thereby offering substantial benefits in rehabilitation, assistive robotics, and hazardous-environment operations.

Conventional robotic control systems primarily depend on physical interfaces such as joysticks, keyboards, and touch-based controllers. Although these systems are effective for able-bodied users, they become impractical for individuals affected by severe motor impairments including paralysis, Amyotrophic Lateral Sclerosis (ALS), and spinal cord injuries [2]. In addition, industrial applications such as chemical handling, radioactive material disposal, and bomb defusal demand remote operation methods that minimize direct human exposure to dangerous environments. These limitations have motivated researchers to explore neuro-robotic systems capable of translating human intention directly into robotic actuation.

Electroencephalography (EEG) has become one of the most widely adopted non-invasive techniques for capturing brain activity in BCI applications due to its safety, portability, and relatively low cost [3]. Recent studies have demonstrated the feasibility of using EEG-based attention levels, eye-blink artifacts, and neural pattern recognition for robotic navigation and prosthetic control [4]. However, many existing systems rely on expensive medical-grade hardware, high

computational requirements, or proprietary platforms that limit accessibility and large-scale deployment. Furthermore, signal latency and noise interference remain major challenges in practical real-time BCI implementations.

To address these limitations, this research proposes *ManoHastha*, a low-cost BCI-driven extendable robotic arm capable of executing mechanical actions based on EEG and Electrooculography (EOG) signals. The system integrates a BioAmp EXG Pill for bio-signal acquisition, an Arduino Nano for signal conditioning, and an ESP32 microcontroller for wireless robotic control. By utilizing attention-based EEG activity and intentional eye blinks as control inputs, the proposed system enables users to perform reach-and-grab operations without physical interaction.

The primary objective of this research is to develop an affordable and reliable neuro-robotic framework suitable for assistive technology and hazardous-environment teleoperation. The study further aims to minimize system latency, improve signal interpretation accuracy, and demonstrate the feasibility of implementing practical BCI-controlled robotic systems using low-cost embedded hardware.

## II. LITERATURE REVIEW

The field of Brain-Computer Interface (BCI) systems has witnessed rapid growth over the past two decades due to increasing interest in intelligent assistive technologies, neuro-robotics, and human-machine interaction. Researchers across the domains of biomedical engineering, robotics, and embedded systems have explored multiple approaches for converting neural activity into meaningful control commands for external devices. Most existing studies primarily focus on rehabilitation support, prosthetic control, and remote robotic manipulation using Electroencephalography (EEG) signals.

Early BCI research concentrated mainly on invasive neural interfaces where electrodes were surgically implanted into the brain to achieve high signal precision and faster response times. Although these systems demonstrated excellent control accuracy, their practical adoption remained limited because of high medical risk, surgical complexity, and elevated implementation costs. Consequently, non-invasive EEG-based approaches gradually became more popular due to their safety, portability, and lower operational requirements [1].

Several researchers investigated EEG-driven robotic systems using consumer-grade headsets such as NeuroSky MindWave and Emotiv EPOC. These studies demonstrated that brainwave patterns associated with attention, relaxation, and motor imagery could be translated into robotic movements and cursor navigation tasks [2]. Wolpaw et al. established foundational BCI methodologies by demonstrating that Alpha and Beta brainwave modulation could reliably support communication between the brain and external machines [3]. Their work significantly contributed to the development of attention-based control systems used in modern neuro-robotic applications.

Another important direction in the literature involves the integration of Electrooculography (EOG) with EEG-based systems. Researchers observed that voluntary eye blinks produce high-amplitude electrical artifacts that are easier to detect compared to weak neural signals [4]. Consequently, several hybrid EEG-EOG frameworks were proposed for wheelchair navigation, robotic grippers, and assistive communication devices. These systems improved reliability by combining cognitive commands with intentional blink-based triggers, thereby reducing false activations and improving overall system stability.

In addition to signal acquisition techniques, significant research has focused on embedded processing architectures for real-time BCI applications. Earlier systems commonly relied on desktop computers or Raspberry Pi platforms for signal processing and robotic control [5]. While these approaches provided adequate computational capability, they often introduced increased latency, higher power consumption, and dependency on complex operating systems. Real-time robotic applications require faster processing with minimal communication delays, especially in hazardous industrial environments where delayed actuation can compromise safety.

Recent studies have therefore explored lightweight microcontroller-based architectures using Arduino boards, ESP32 modules, and wireless communication systems for portable BCI implementations [6]. These systems aimed to reduce overall hardware complexity and improve affordability. However, many existing implementations still suffer from limitations such as unstable wireless communication, insufficient noise filtering, poor signal classification accuracy, and restricted scalability for multi-degree-of-freedom robotic systems.

A critical review of the existing literature reveals a major research gap in the development of affordable, real-time, and reliable BCI robotic systems suitable for widespread deployment. Most high-performance medical-grade systems remain financially inaccessible for educational institutions, small research laboratories, and developing regions. Furthermore, many commercial BCI platforms operate using proprietary “black-box” algorithms, limiting customization and experimental flexibility for researchers and students.

The proposed *ManoHastha* system addresses these limitations through a low-cost hybrid architecture that combines EEG and EOG signal interpretation with efficient embedded

processing. Unlike earlier systems dependent on computationally intensive platforms, the proposed framework utilizes an Arduino Nano for signal acquisition and conditioning, while an ESP32 microcontroller performs wireless communication and robotic actuation. This separation of processing tasks minimizes latency and improves operational reliability.

Another distinguishing feature of the proposed work is its focus on practical real-world usability. Instead of relying solely on complex thought classification algorithms, the system interprets attention levels and intentional eye blinks as primary control inputs. This approach simplifies signal processing while maintaining reliable robotic control performance. Additionally, the robotic manipulator is designed as a wireless multi-degree-of-freedom system capable of performing reach-and-grab operations in hazardous environments and assistive scenarios.

Therefore, the present research contributes to the broader field of neuro-robotics by demonstrating that effective BCI-driven robotic control can be achieved using affordable and accessible hardware components. The study highlights a scalable and practical framework that bridges the gap between academic BCI research and real-world implementation, thereby supporting future developments in assistive healthcare technologies, industrial teleoperation, and intelligent robotic systems.

### III. METHODOLOGY

The proposed *ManoHastha* system was developed using an experimental research methodology focused on the design, implementation, and evaluation of a Brain-Computer Interface (BCI)-driven robotic manipulator. The study adopted a hardware-software co-design approach to establish reliable communication between neural signal acquisition modules and robotic actuation mechanisms. The methodology was structured into four major stages: bio-signal acquisition,

signal processing, wireless communication, and robotic actuation.

#### A. System Architecture Design

The overall system architecture was divided into two functional units: the Signal Acquisition Unit (Transmitter) and the Actuation Unit (Receiver). This modular design was implemented to isolate sensitive bio-signal processing circuitry from the electrical noise generated by high-current servo motors. The Signal Acquisition Unit consisted of the BioAmp EXG Pill v2, Arduino Nano, and HC-05 Bluetooth module, while the Actuation Unit comprised the ESP32 DevKit V1, Logic Level Converter, MG996R servo motors, and regulated power supply circuitry.

#### B. Bio-signal Acquisition Procedure

The biological signals were collected using non-invasive gel electrodes positioned on the user's forehead near the prefrontal cortex region (Fp1 placement). The BioAmp EXG Pill v2 was utilized as the primary analog front-end for capturing Electroencephalography (EEG) and Electrooculography (EOG) signals. Since neural signals are naturally weak and highly susceptible to environmental interference, the BioAmp module amplified and filtered the incoming signals before transmitting them to the Arduino Nano.

The Arduino Nano performed Analog-to-Digital Conversion (ADC) by continuously sampling the analog waveform from the BioAmp output pin. Initial signal conditioning and threshold-based preprocessing were implemented within the microcontroller firmware using Embedded C++ programming through the Arduino IDE environment.

### C. Signal Processing and Command Generation

The proposed methodology employed a hybrid artifact-based control strategy using both EEG attention levels and EOG blink detection. Rather than relying on computationally intensive machine-learning classification models, the system utilized threshold-based signal interpretation to improve reliability and reduce processing latency.

Intentional eye blinks generated high-amplitude EOG spikes that exceeded predefined threshold voltages and were interpreted as “Grab” or “Release” commands. Simultaneously, sustained attention levels were detected by monitoring changes associated with Beta-wave dominance during focused mental activity. When the measured attention signal crossed the configured threshold value, extension and reach commands were generated for the robotic arm.

The processed digital commands were transmitted wirelessly through the HC-05 Bluetooth module to the ESP32-based robotic controller.

### D. Wireless Communication and Robotic Actuation

The ESP32 DevKit V1 functioned as the central processing controller for robotic actuation. Wireless data packets received through Bluetooth communication were decoded and converted into Pulse Width Modulation (PWM) signals for servo motor control. Four MG996R high-torque servo motors were utilized to provide multi-degree-of-freedom movement including base rotation, arm extension, joint movement, and gripper operation.

A Logic Level Converter was incorporated between the ESP32 and servo control circuitry to ensure safe bidirectional voltage conversion between 3.3V and 5V logic levels. Separate power rails were maintained for the control circuitry and motor supply to avoid voltage fluctuations

and electrical interference during high-load operation.

### E. Experimental Testing and Performance Analysis

The implemented prototype was experimentally evaluated under multiple operational scenarios to analyze system responsiveness, signal accuracy, and actuation reliability. Testing procedures included:

- EEG attention detection experiments,
- EOG blink recognition tests,
- Wireless latency analysis,
- Servo motor response evaluation,
- Payload handling assessment.

Latency measurements were obtained by calculating the time difference between neural signal detection and corresponding robotic movement. Experimental observations indicated an average total system latency of approximately 125 milliseconds, enabling near real-time teleoperation performance.

### F. Software and Development Tools

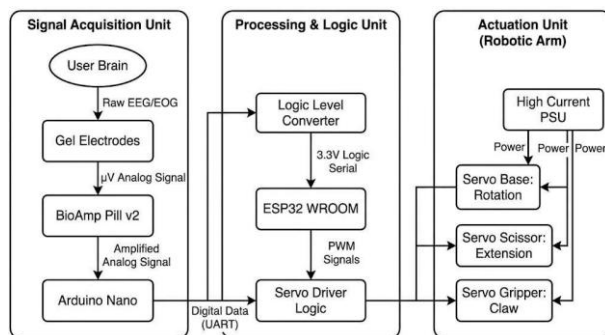
The complete system firmware was developed using the Arduino IDE platform with Embedded C++ programming. Serial communication debugging and real-time signal visualization were performed during calibration and testing phases. Signal filtering and threshold optimization techniques were implemented directly within the embedded environment to reduce dependency on external computational systems.

### G. Ethical and Safety Considerations

Since the study involved non-invasive bio-signal acquisition, proper safety precautions were maintained throughout experimentation. The electrodes used in the system did not penetrate

the skin and operated under safe low-voltage conditions. Participants involved in preliminary testing were informed about the experimental procedure before signal acquisition. Additionally, electrical isolation between the bio-signal acquisition unit and robotic power circuitry was maintained to ensure user safety during operation.

The proposed methodology demonstrates that reliable BCI-based robotic control can be achieved using low-cost embedded hardware while maintaining acceptable levels of responsiveness, safety, and operational accuracy suitable for assistive and industrial teleoperation applications.



#### IV. RESULTS AND DISCUSSION

The developed *ManoHashta* system was experimentally evaluated to examine the efficiency of bio-signal acquisition, command interpretation, wireless communication, and robotic actuation. The results obtained during testing confirmed that the proposed low-cost Brain-Computer Interface (BCI) framework could perform reliable robotic operations using EEG and EOG signals in near real-time conditions.

During experimentation, the Bio-Amp EXG Pill successfully captured and amplified weak neural and ocular signals from the user's forehead region. The system effectively differentiated intentional eye blinks from normal involuntary eye movements by applying predefined threshold values. Intentional hard blinks consistently

generated distinct high-amplitude signal spikes, allowing the robotic gripper to execute grab and release operations accurately. Minor facial movements and environmental noise were successfully ignored, which improved the overall reliability of the control mechanism.

The EEG-based attention detection mechanism also demonstrated stable performance during testing. Users were instructed to maintain concentration on a target object, and the system monitored variations associated with focused mental activity. When the detected attention level crossed the programmed threshold, the robotic arm initiated extension and movement operations. The results indicated that the threshold-based approach provided consistent performance without requiring computationally intensive machine-learning algorithms.

Wireless communication between the Arduino Nano transmitter unit and the ESP32 receiver module remained stable throughout continuous operation. The hybrid processing architecture significantly reduced system delay by separating signal acquisition from robotic actuation tasks. Experimental observations showed that the complete signal-to-action response occurred within an average latency of approximately 125 milliseconds, providing smooth and responsive teleoperation performance suitable for practical applications.

The mechanical performance of the robotic manipulator was also found to be satisfactory. The MG996R servo motors provided stable multi-degree-of-freedom movement including arm rotation, extension, and gripping actions. The separate power regulation arrangement prevented voltage fluctuations during heavy-load operation and maintained consistent actuator response without noticeable jitter or communication failure.

Compared to several earlier BCI robotic systems that relied on expensive medical-grade equipment or high-power processing platforms, the proposed *ManoHashta* framework achieved comparable functional performance using affordable embedded hardware. Existing studies frequently reported limitations related to latency, portability, and implementation cost. In contrast, the proposed system demonstrated that effective neuro-robotic control could be achieved using a lightweight and low-cost architecture without compromising operational reliability.

Overall, the obtained results validate the feasibility of integrating EEG attention detection and EOG blink recognition into an accessible robotic control framework. The system successfully fulfilled its intended objective of enabling intuitive human-machine interaction through non-invasive neural interfaces. The findings further highlight the potential of the proposed approach for future applications in assistive healthcare systems, rehabilitation technologies, and hazardous-environment robotic teleoperation.

## HARDWARE IMPLEMENTATION

- BioAmp EXG Pill v2 was used for acquiring and amplifying EEG and EOG bio-signals.
- Arduino Nano performed analog-to-digital conversion and initial signal conditioning.
- HC-05 Bluetooth module enabled wireless transmission of processed signals.
- ESP32 DevKit V1 acted as the main controller for robotic movement and command execution.
- MG996R servo motors provided multi-degree-of-freedom robotic arm movement.
- Logic Level Converter ensured safe communication between 3.3V and 5V devices.
- L7805 voltage regulator maintained stable power supply for control circuitry.

- A 7.4V Li-ion battery pack powered both the robotic system and embedded controllers.

## V. SOFTWARE IMPLEMENTATION

- Arduino IDE was used for firmware development and system programming.
- Embedded C++ was used for coding signal processing and robotic control logic.
- Threshold-based algorithms were implemented for EEG attention and EOG blink detection.
- PWM signal generation was used for accurate servo motor positioning.
- Serial communication protocols enabled wireless data transfer between controllers.
- Real-time signal monitoring and debugging were performed during calibration and testing.
- Embedded processing techniques reduced latency and improved system responsiveness.

## VI. APPLICATIONS

The proposed *ManoHashta* system has significant potential in various real-world applications involving assistive technology, industrial automation, healthcare, and intelligent robotics. One of its primary applications is in assistive systems for individuals suffering from paralysis, spinal cord injuries, or severe motor impairments, where users can control robotic devices using brain and eye signals without physical movement. The system can also be utilized in medical rehabilitation environments to help patients interact with external devices during recovery and neurotherapy sessions.

In industrial and hazardous environments, the robotic arm can assist in handling dangerous materials, chemical substances, radioactive components, or explosive devices while keeping human operators at a safe distance. This makes

the system highly suitable for defence operations, bomb disposal tasks, and disaster-response applications. Additionally, the proposed framework can support remote teleoperation in manufacturing industries where direct human intervention may involve operational risks.

The developed neuro-robotic architecture can further be extended for smart prosthetic control, enabling advanced prosthetic limbs to respond to neural activity. In the field of research and education, the system serves as an affordable experimental platform for students and researchers working in Brain-Computer Interfaces, embedded systems, neuroscience, and robotics. Furthermore, the underlying neural control mechanism can be integrated into smart home automation systems, allowing physically challenged individuals to operate household appliances through cognitive commands. Overall, the proposed system demonstrates wide applicability across healthcare, industrial safety, rehabilitation, defence, and intelligent automation domains.

## VII. CONCLUSION

The present study successfully demonstrated the design and implementation of *ManoHastha*, a low-cost Brain-Computer Interface (BCI)-driven robotic arm capable of performing robotic operations using EEG and EOG signals. By integrating the BioAmp EXG Pill, Arduino Nano, ESP32 microcontroller, and wireless communication modules, the system established an effective bridge between human neural activity and mechanical actuation. The proposed framework achieved reliable attention-based movement control and accurate blink-triggered operations while maintaining low processing latency and stable robotic performance.

One of the major contributions of this research lies in its affordability and accessibility. Unlike conventional medical-grade BCI systems that require expensive hardware and complex computational infrastructure, the proposed system demonstrated that practical neuro-robotic control can be achieved using cost-effective embedded components. The hybrid processing architecture further improved real-time

responsiveness by separating signal acquisition and robotic actuation tasks, thereby reducing communication delays and improving operational reliability.

The findings of this study highlight the growing potential of non-invasive BCI systems in assistive healthcare, rehabilitation technologies, industrial teleoperation, and hazardous-environment applications. The developed system provides an accessible platform for future research in human-machine interaction and intelligent robotics.

Although the current implementation focused primarily on threshold-based EEG and EOG signal interpretation, future work can extend the system using advanced machine-learning algorithms for improved neural pattern recognition and adaptive control. Further enhancements may include wireless cloud integration, multi-user support, higher-degree robotic manipulators, and integration with artificial intelligence for autonomous decision-making. These improvements could significantly expand the practical applicability of affordable BCI-driven robotic systems in real-world environments.

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