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## Brain-Computer Interface Controlled Robot Navigation for Quality Inspection in Industry

<sup>1</sup>Prof. Seema Khamankar,

<sup>2</sup>Kunal Naik,

<sup>3</sup>Owais Nadaf,

<sup>4</sup>Aman Hannure,

<sup>5</sup>Mahtab Ali Siddiquee

<sup>1</sup> Assistant Professor, Ajeenkya D Y Patil School of Engineering, Pune, INDIA

<sup>2-5</sup> UG students, Ajeenkya D Y Patil School of Engineering, Pune, INDIA

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### Abstract:

This paper presents the design and implementation of a Brain–Computer Interface (BCI)–based robotic arm integrated with a conveyor system for industrial automation and assistive applications. The proposed system aims to enable hands-free interaction with industrial machinery, particularly benefiting differently abled individuals by reducing dependence on physical input devices. Electroencephalogram (EEG) signals are acquired non-invasively from the scalp using gel electrodes and amplified for analysis. The amplified EEG signals are transmitted to an Arduino Uno microcontroller.

Relevant features are extracted from the processed EEG signals to distinguish between relaxed and focused mental states, which are mapped to predefined control commands. Based on the detected cognitive state, the system generates real-time actuation signals to control a robotic arm operating alongside a conveyor belt. A focused mental state triggers the robotic arm to reject defective products from the conveyor system, while a relaxed state maintains normal operation. The results demonstrate consistent mental state recognition with low latency, validating the feasibility of implementing low-cost BCI systems in industrial environments. The proposed framework highlights the potential of integrating BCI technology with industrial automation to create accessible, intelligent, and human-centric manufacturing systems.

**Keywords:** Electroencephalogram (EEG), Industrial Automation, Robotic Arm Control, Conveyor System, Signal Processing

## 1.Introduction

In recent years, the rapid advancement of industrial automation and intelligent manufacturing systems has significantly transformed traditional production environments [1]. Automation technologies such as robotic arms, conveyor systems, and sensor-based inspection mechanisms have improved productivity, precision, and safety across various industrial sectors. However, despite these advancements, most industrial control systems continue to rely heavily on manual input devices such as switches, joysticks, keyboards, and touch-based interfaces. These conventional interaction methods pose limitations for individuals with physical disabilities and can also lead to operator fatigue, safety risks, and reduced efficiency in complex industrial environments.

Brain–Computer Interface (BCI) technology has emerged as a promising solution to bridge the communication gap between human cognitive intent and machine control [2]. A BCI system enables direct interaction between the human brain and external devices by interpreting brain signals, primarily electroencephalogram (EEG) signals, without requiring physical movement. EEG-based BCIs are non-invasive, relatively low-cost, and suitable for real-time applications, making them attractive for assistive technologies and industrial automation systems.

The integration of BCI technology into industrial automation holds significant potential, particularly in environments where precision, safety, and accessibility are critical. For differently abled individuals, traditional industrial roles often remain inaccessible due to physical constraints, despite the availability of advanced machinery. A BCI-driven control mechanism can empower such individuals to actively participate in industrial operations by enabling hands-free and effort-free control of machines [3]. Moreover, even for able-bodied operators, BCI-based systems can reduce cognitive and physical workload, minimize human error, and enhance overall operational safety.

Robotic arms integrated with conveyor systems are widely used in industries for tasks such as sorting, inspection, material handling, and defect rejection [4]. These systems typically rely on vision sensors, proximity sensors, or manual supervision to identify defective products. While effective, such approaches may require constant human intervention or complex sensor fusion techniques. Incorporating human cognitive input through a BCI adds an additional layer of intelligent decision-making, allowing the operator’s mental focus to directly influence system behavior in real time.

In this context, EEG signals corresponding to different mental states—such as relaxation and concentration—can be effectively utilized to generate control commands. Focused mental states often reflect increased cognitive engagement and can be mapped to active control actions, while relaxed states can represent idle or standby modes. Accurate acquisition and interpretation of these signals require reliable amplification and preprocessing, as EEG signals are inherently low in amplitude and susceptible to noise. The Bio Amp EXG Pill serves as an effective solution for amplifying EEG signals obtained through gel electrodes, ensuring sufficient signal quality for downstream processing [5].

Microcontroller platforms such as the Arduino Uno offer a cost-effective and flexible solution for real-time signal processing and control implementation. By performing basic filtering,

feature extraction, and classification, the microcontroller can translate EEG-derived mental states into actionable control signals for actuating a robotic arm. Despite growing research interest in BCI systems for medical rehabilitation and assistive communication, their application in industrial automation remains relatively limited, particularly in practical conveyor-based environments [6]. This paper addresses the above challenges by proposing a BCI-based robotic arm integrated with a conveyor system for industrial assistance and automation.

Despite advancement in Brain-Computer Interface (BCI) systems for assistive and robotic control applications, several challenges remain in deploying them in real-world industrial environments. Issues such as EEG signal noise, inter-subject variability and the need for computationally efficient processing can affect system's reliability and real time performance. Addressing these challenges require simple and efficient signal processing techniques along with lightweight control frameworks suitable for low-cost embedded systems.

## 2. Survey Methodology

This review follows a systematic approach to identify, select, and analyze research on Brain-Computer Interface (BCI) systems for robotic arm control and industrial automation applications. The goal is to provide an overview of techniques, signal acquisition methods, and classification algorithms for EEG-based motor control and defect rejection systems.

- A. Data Sources and Search Strategy:** Papers were collected from IEEE Xplore, Science Direct, Springer Link, MDPI, and Google Scholar using keywords like "Brain-Computer Interface," "EEG," "Robotic Arm Control," "Industrial Automation," "Conveyor System," and "Assistive Technology," combined with Boolean operators for relevance [7].
- B. Inclusion and Exclusion Criteria**  
**Inclusion:** Studies from 2002–2025 applying BCI/EEG for robotic control or industrial automation with experimental, simulation, or real-time results. **Exclusion:** Non-BCI studies, papers with insufficient methodology or results, duplicates, and non-peer-reviewed articles.
- C. Review:** Approach selected papers were analyzed for: BCI type (non-invasive), data acquisition (EEG electrodes), signal preprocessing, feature extraction/classification, model performance (accuracy, precision, recall), and practical implementation challenges. Information was categorized to highlight trends, advantages, limitations, and research gaps [8].
- D. Outcome:** The survey provides a clear view of the state-of-the-art in BCI-based robotic control for industrial applications, offering comparative insights on algorithms, sensor usage, and deployment frameworks, while identifying areas for future research.

## 3. Literature Survey:

Wolpaw et al., (2002) demonstrated the feasibility of using electroencephalogram (EEG) signals for non-invasive BCI systems, primarily targeting communication and assistive technologies for individuals with severe motor impairments [1]. Although this work established core principles of EEG signal acquisition and interpretation, it was largely confined to clinical

and laboratory environments, with minimal consideration of real-time industrial deployment [1]. Millán et al., (2010) proposed mental state-based control mechanisms for robotic devices, showing that cognitive states such as concentration and relaxation can be mapped to control commands. However, these systems required extensive user training and complex classification algorithms, which limit their scalability and practicality in industrial environments [2].

Rebsamen et al., (2010) developed an EEG-controlled robotic arm capable of performing basic manipulation tasks. While the system demonstrated acceptable performance, it relied on computationally intensive processing and was sensitive to EEG noise and artifacts, resulting in increased latency and reduced reliability [3]. Gonzalez and Woods, (2018) highlighted the effectiveness of image-processing-based inspection systems for defect detection. Nevertheless, these systems depend heavily on controlled environmental conditions, regular calibration, and sensor maintenance, which increases system complexity and operational cost [4].

Endsley et al., (2019) discussed human-in-the-loop frameworks that allow operators to supervise automated processes. Although such approaches enhance situational awareness, they continue to rely on physical interaction through graphical interfaces, keyboards, or gesture-based inputs, thereby limiting accessibility for differently abled individuals [5]. Nijholt et al., (2020) demonstrated lightweight BCI systems using microcontrollers for basic control applications. While these implementations validate the feasibility of embedded BCI architectures, their applications are largely limited to proof-of-concept demonstrations such as cursor control or simple device switching, with little focus on real industrial automation tasks [6]. Chamola et al., (2020) provided a comprehensive review of BCI technologies and applications, emphasizing the need for low-cost, real-time implementations suitable for industrial environments [7].

#### **4. GAP Analysis:**

The gap analysis of existing research on BCI-based robotic control highlights several critical limitations and opportunities for future work. Although numerous studies have demonstrated progress in areas such as EEG signal acquisition, mental state classification, and assistive robotic control, most research remains focused on clinical or laboratory settings, which limits the generalizability of the models across diverse industrial environments.

**Table I.** Literature Survey Findings

<b>Author(s)</b>	<b>Year</b>	<b>Focus Area</b>	<b>Key Contribution</b>	<b>Limitations</b>
Wolpaw et al.	2002	BCI Fundamentals	Established non-invasive EEG-based BCI principles	Limited to clinical settings
Millán et al.	2010	Robotic Control	Mental state mapping to commands	Extensive user training required
Rebsamen et al.	2010	Robotic Arm Control	Demonstrated EEG-controlled manipulation	High latency, noise sensitivity
Gonzalez & Woods	2018	Defect Detection	Image-processing inspection systems	Complex calibration, high cost
Endsley et al.	2019	Human-in-the-Loop	Operator supervision frameworks	Physical interaction still required
Nijholt et al.	2020	Embedded BCI	Microcontroller-based BCI systems	Limited to simple demonstrations
Chamola et al.	2020	BCI Review	Comprehensive technology overview	No industrial implementation
Douibi et al.	2021	Industry 4.0	BCI for manufacturing systems	Practical implementation limited
Arshad et al.	2022	Robotic Assistive	EEG-based intelligent robotic control	Computational complexity
Ding et al.	2023	Robotic Hand Control	Real-time EEG-based robotic hand	High processing requirements

Scalability and real-time deployment of BCI solutions are still underexplored, particularly for large-scale industrial operations or resource-constrained settings, where efficient computation and reduced model complexity are essential. While deep learning techniques show significant potential for improving classification accuracy and predictive performance, these methods are not yet widely implemented in embedded systems, and their integration with real-time IoT systems remains limited.

**Table II.** GAP Analysis

<b>Sr. No.</b>	<b>Gap Area</b>	<b>Description</b>
1	Industrial Deployment	Most BCI systems are confined to clinical or laboratory environments
2	Scalability	Limited research on large-scale industrial BCI implementation
3	Computational Complexity	High processing requirements limit embedded deployment
4	Noise Robustness	Insufficient handling of motion artifacts and environmental interference
5	Real-time Performance	Latency and reliability issues in continuous operation
6	Cost-Effectiveness	Many systems rely on expensive, high-end equipment

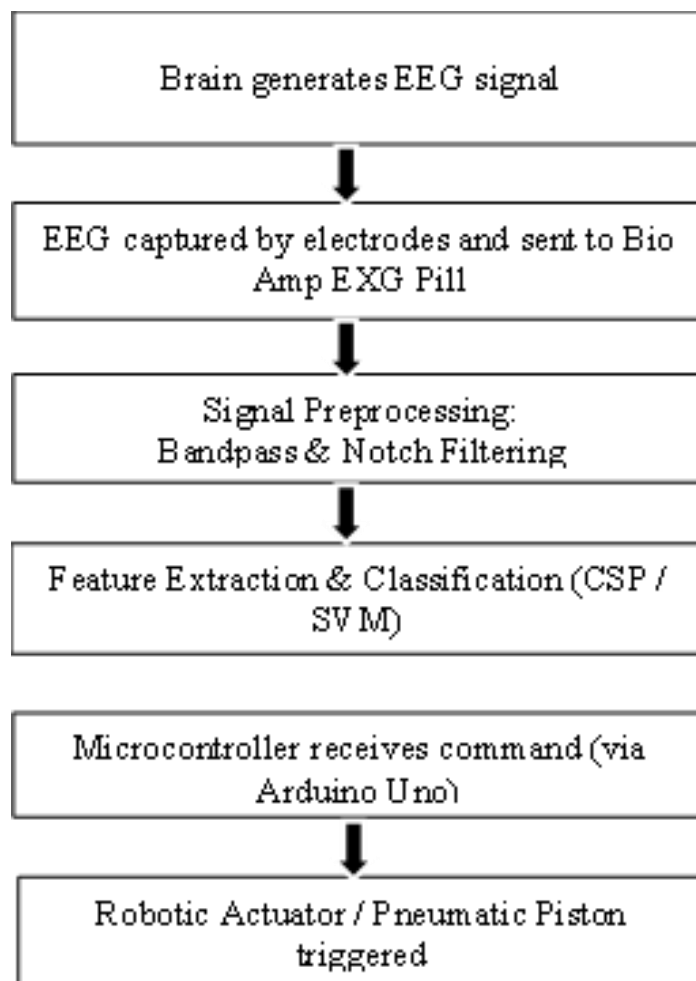
Overall, these gaps indicate a pressing need for comprehensive, scalable, and explainable BCI-based control frameworks that can operate reliably in real-world industrial environments, integrating advanced sensor data, edge computing, and low-cost hardware to enhance efficiency, reduce costs, and improve accessibility.

### **5. Proposed System:**

The methodology for developing a Brain-Computer Interface (BCI)-based robotic arm control system for industrial defect rejection focuses on a systematic approach to EEG signal acquisition, processing, classification, and actuation. The proposed system integrates non-invasive EEG sensors, embedded processing, and lightweight classification algorithms to translate human cognitive intent into robotic actions.

Key stages of the methodology involve collecting EEG signals from the user's scalp using gel electrodes and the Bio Amp EXG Pill amplifier. The collected data is pre-processed to remove

noise and extract meaningful features through filtering and statistical analysis. These features are then used to classify mental states (relaxed or focused) using rule-based decision logic. The methodology further involves model evaluation using performance metrics such as precision, recall, accuracy, and F1-score to ensure reliability. Once validated, the trained model is deployed alongside real-time monitoring hardware to continuously evaluate user intent and generate actuation signals for the robotic arm. This structured methodology ensures accurate fault detection, reduced unplanned downtime, and improved operational efficiency in industrial environments[9].



**Fig. 3.** Block diagram of proposed system

**A. Software Requirement:**

- Operating System: Windows 10 / Linux (Ubuntu)
- Programming Language: Python 3.x / Embedded C/C++
- Development Environment: Arduino IDE
- Data Processing & Analysis Libraries: NumPy, Pandas, SciPy

- Machine Learning Libraries: Scikit-learn (for offline training)
- Data Visualization Tools: Matplotlib, Seaborn
- Database Management: MySQL / SQLite (for sensor data and logs)

## B. Algorithm

- Input: EEG signals from gel electrodes via Bio Amp EXG Pill

### Flow chart description:

Acquire Data:

Collect EEG signals from scalp electrodes using Bio Amp EXG Pill.

Pre-process Data: Clean, filter, and prepare the data for analysis.

Develop Model: Extract key features showing mental state.

Train Model: Use machine learning to classify mental states (relaxed/focused).

Deploy & Integrate: Implement the trained model in real systems for real-time robotic arm actuation and defect rejection.

## 6. Applications:

**Manufacturing Plants:** Checking product quality and removing defective items on a conveyor belt, so workers don't need to handle them manually during the assembly process.

**Automotive Industry:** Assisting in quality control tasks for vehicle components, particularly beneficial for workers with physical limitations.

**Electronics Manufacturing:** Carefully checking circuit boards and electronic parts using smart, automated control systems.

**Food Processing Industry:** Checking quality in a clean and safe way, where touching by hand could cause contamination.

**Pharmaceutical Industry:** Sterile environment quality control where minimizing human contact is essential.

**Assistive Technology:** Enabling differently abled individuals to participate in industrial quality inspection roles previously inaccessible to them.

**Smart Factories (Industry 4.0):** Integration with IoT-enabled manufacturing systems for real-time cognitive control and automated quality assurance.

## 7. Conclusion:

This study demonstrated a practical framework for enabling hands-free operation of an industrial manipulator using neural activity. The proposed approach translates cognitive intent into mechanical action through embedded processing and simplified control logic, ensuring reliable operation without heavy computational requirements. By continuously monitoring EEG signals corresponding to relaxed and focused mental states, the system can detect user intent, predict desired actions, and control the robotic arm with high precision. Compared to traditional manual inspection methods, this BCI-based predictive approach significantly reduces reliance on physical input devices, enhances accessibility for differently abled

individuals, minimizes operator fatigue, and ensures uninterrupted production processes. The adaptability of the classification models allows the system to handle diverse users, varying cognitive patterns, and complex industrial environments, making it highly scalable and robust. Moreover, the integration of BCI technology into industrial workflows supports the transition toward Industry 4.0 by enabling data-driven decision-making, optimized resource utilization, and improved overall operational efficiency. Overall, this project highlights the transformative potential of combining artificial intelligence, brain-computer interfaces, and industrial automation technologies to create intelligent, accessible, and human-centric manufacturing systems that can revolutionize modern industrial practices and promote sustainable, inclusive manufacturing operations [10].

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