<u>XIMO</u>
<u>An Industrial Robotic Arm</u>

S.Y (Electronics and Telecommunication)

Coner-Stone Project Report

submitted by

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ABSTRACT

In the era of Industry 4.0, robotic automation has emerged as a transformative force, especially in manufacturing and industrial environments. Robotic arms, in particular, play a vital role in automating tasks that are repetitive, precise, hazardous, or require consistent accuracy. This project, titled XIMO – An Industrial Robotic Arm, presents the design, development, and implementation of a 5-Degree-of-Freedom (DOF) robotic arm aimed at industrial applications such as pick-and-place operations, sorting, and object manipulation.

The mechanical design was created using SolidWorks, a professional-grade CAD tool that allowed detailed modeling of the arm's structure, including the base, shoulder, elbow, and gripper joints. The design aimed for a lightweight yet rigid structure to minimize servo load while maximizing range of motion and precision. The 4-DOF configuration enables the arm to perform complex tasks with multiple joint movements. The actuation system consists of four servo motors, each designated to a specific axis of movement, ensuring controlled and repeatable motion suitable for industrial use.

On the electronics front, the system is built around the powerful ESP32 microcontroller, known for its integrated Wi-Fi and Bluetooth capabilities. Two ESP32 boards were used—one for the transmitter and one for the receiver. The communication between them is established using the ESP-NOW protocol, which is ideal for low-latency, peer-to-peer, connectionless communication. This setup allows real-time control of the robotic arm without the delays or pairing complexities associated with traditional Bluetooth or Wi-Fi protocols.

A significant contribution of this project is the custom PCB design for both the transmitter and receiver units, created using Altium Designer. The PCBs are compact and designed to integrate essential components such as ESP32 headers, servo connections, power regulators, and an OLED interface. These boards minimize wiring clutter and improve system reliability and durability.

An OLED display module is integrated on the transmitter side to provide user feedback such as connection status, operational mode, and error messages. This not only improves user interaction but also aids in debugging and monitoring the system during operation.

The power supply system is designed to meet the demands of the servo motors while isolating logic-level components to avoid voltage fluctuations. A regulated 5V supply ensures consistent and safe power delivery, contributing to the overall stability of the robotic system.

Testing and validation of XIMO were conducted in a controlled lab environment. The system demonstrated excellent responsiveness, with smooth servo actuation and precise movement. The wireless range of communication was tested up to 15 meters with minimal latency. The modular nature of the arm also allows for future expansions, such as increasing the number of DOFs or integrating feedback sensors like encoders or force sensors.

In conclusion, XIMO serves as a robust and scalable prototype for wireless industrial robotic arms. Its design emphasizes affordability, ease of assembly, modularity, and wireless control—all essential for modern automation systems. The successful integration of SolidWorks-based mechanical design, ESP32-based wireless control, and custom PCB development makes XIMO a compelling example of cross-domain engineering. In future iterations, the project can be extended to include AI-driven computer vision, autonomous decision-making, and IoT connectivity for real-time monitoring and remote control.

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1. INTRODUCTION

1.1 Background

The fourth industrial revolution, commonly referred to as Industry 4.0, has drastically transformed manufacturing and production environments through the integration of advanced technologies such as robotics, artificial intelligence (AI), Internet of Things (IoT), and cloud computing. At the heart of this transformation lies automation, which has enabled industries to improve productivity, precision, and efficiency while minimizing human intervention and associated risks.

One of the most prominent elements in industrial automation is the **robotic arm**, a programmable electromechanical device that mimics the functions of a human arm. These arms can be designed with varying degrees of freedom (DOF), allowing them to perform tasks such as assembling, sorting, welding, painting, pick-and-place, and packaging. High-end robotic systems are widely adopted in large-scale manufacturing industries such as automotive, electronics, and aerospace. However, these solutions are often expensive, require complex setup procedures, and involve proprietary hardware and software, which makes them inaccessible to small and medium enterprises (SMEs), educational institutions, and research labs with limited budgets.

This gap in affordability and accessibility has led to a growing interest in **low-cost, modular, and user-friendly robotic arms** that can be tailored for specific tasks. Recent advancements in microcontrollers, wireless communication, 3D modeling, and rapid prototyping have opened the door to the development of such systems. Specifically, microcontrollers like the **ESP32** offer high-performance computing capabilities along with built-in Wi-Fi and Bluetooth functionalities at a very low cost. This makes them ideal candidates for embedded robotic applications that require both control and wireless connectivity.

Moreover, software platforms such as **SolidWorks** have revolutionized mechanical design by offering highly accurate simulations and stress analysis before actual fabrication. In parallel, tools like **Altium Designer** allow designers to create custom printed circuit boards (PCBs), thereby ensuring clean and efficient electronic layouts that are easier to assemble and debug compared to breadboard-based systems.

Recognizing this potential, our team conceptualized **XIMO – An Industrial Robotic Arm**. The objective of this project was to design and build a cost-effective, wirelessly-controlled 4-DOF robotic arm using readily available components and tools. XIMO is intended to serve as a prototype for industrial tasks such as object handling and positioning, with a focus on modularity, wireless control, and real-time feedback.

1.2 Problem Statement / Aim

While robotic arms are increasingly deployed in industrial environments, a significant challenge persists: **the lack of affordable, modular, and customizable robotic arms tailored to low-volume, application-specific industrial tasks.** Most commercially available robotic arms are built for heavy-duty operations and are equipped with complex hardware and software systems that require specialized training to operate. This renders them unsuitable for:

- Educational institutions looking to teach robotics through hands-on learning.
- SMEs seeking automation solutions without heavy capital expenditure.
- Research labs aiming to prototype new robotic applications rapidly.

Furthermore, a majority of available DIY robotic arm kits are limited in capabilities—they often lack precision, wireless control, real-time feedback mechanisms, and mechanical robustness. These limitations restrict their real-world usability, confining them to hobbyist or demonstration-level applications.

The core **aim** of this project is to bridge this gap by developing **XIMO**, a robotic arm that is:

- Compact and lightweight
- Easy to assemble and operate
- Wirelessly controlled using low-latency protocols
- Designed using industry-standard tools (SolidWorks and Altium)
- Equipped with user feedback features (OLED display)

By achieving these objectives, the project intends to contribute a working prototype that can serve both academic and light-industrial applications.

1.3 Objectives

To transform this concept into reality, the project was structured around the following major objectives:

- **Mechanical Design:**
  - Develop a CAD model of a 5-DOF robotic arm using SolidWorks.
  - Optimize the design for ease of 3D printing or CNC fabrication.
  - Ensure mechanical joints allow smooth articulation using standard servo motors.
- **Electronic Control System:**
  - Select a suitable microcontroller capable of wireless communication and PWM control—ESP32 was chosen.
  - Implement real-time wireless communication using **ESP-NOW**, an efficient peer-to-peer protocol that eliminates the need for Wi-Fi networks.
  - Integrate an OLED display to provide real-time status updates such as signal strength, command mode, and feedback from sensors (if any).
- **Custom PCB Design:**
  - Design transmitter and receiver PCBs using Altium Designer.
  - Include components such as ESP32 headers, servo connections, voltage regulators, and I2C communication pins.
  - Minimize wiring complexity and ensure compact layout for enclosure integration.
- **Wireless Control Interface:**
  - Controlling the Arm through mobile by using IP Address.
  - Created a web server.
- **System Integration and Testing:**

    - Assemble the robotic arm and integrate it with the custom PCBs.
    - Perform functional testing to validate wireless communication, motor control, and response time.
    - Evaluate range, latency, and accuracy of servo movements.
- **Documentation and Scalability:**
    - Maintain a clear and structured documentation process to support future enhancements.
    - Explore potential for increasing the number of DOFs or adding sensors like encoders, force sensors, or cameras.

These objectives reflect a multidisciplinary approach, incorporating mechanical design, embedded systems, electronics, and wireless communication.

1.4 Scope of the Project

The **scope** of the XIMO project includes the design, fabrication, and testing of a **5-DOF industrial robotic arm** with wireless control capability. The system is built to be modular, allowing for future expansions and customizations. The scope covers:

- **Mechanical Modeling:** Using SolidWorks for complete kinematic modeling, joint constraints, and motion analysis.
- **Wireless Embedded System:** Using ESP32 modules for both control and actuation via low-latency communication protocols.
- **Custom PCBs:** Fabrication-ready transmitter and receiver boards using Altium to reduce size, weight, and clutter.
- **User Feedback Mechanism:** OLED integration for operational transparency and diagnostics.
- **Testing and Validation:** Real-time control testing in lab conditions, including range, load capacity, and movement smoothness.

Future Scope:

- Add **vision-based AI control** using camera modules and computer vision.
- Add ROS and deep learning .
- Integrate with **IoT dashboards** for remote monitoring and control.
- Include **sensor feedback loops** for precision-based applications like automated welding or quality control.

2.REVIEW OF RELEVANT LITERATURE

Robotic arms have been extensively studied and implemented in industrial automation, healthcare, agriculture, and academic research. The core function of a robotic arm is to mimic the range of motion and dexterity of a human arm, enabling it to perform complex, repetitive, or hazardous tasks with high precision. Over the years, advancements in materials science, microcontrollers, sensor technology, and embedded systems have significantly expanded the design possibilities and cost-efficiency of such systems.

2.1 Evolution and Applications of Robotic Arms

Historically, industrial robots were large, rigid, and expensive systems primarily used in automotive assembly lines for welding, painting, or placing heavy components. Early implementations used pneumatic or hydraulic actuators due to their high torque capabilities, but they lacked accuracy and were prone to mechanical failure. As technology evolved, servo motor-driven arms became more common for lighter applications, offering better accuracy and programmability.

Modern robotic arms are increasingly becoming modular and user-configurable. In addition to industrial applications, robotic arms are now used in:

Medical procedures, such as robotic surgeries (e.g., Da Vinci system).

Agricultural automation, for tasks like fruit picking.

Education and research, where robotic arms serve as an introductory platform for mechatronics and control systems.

Logistics and warehouse automation, for sorting, packaging, and material handling.

The trend toward low-cost, wireless-controlled robotic systems has opened doors for smaller industries and academic institutions to experiment with automation without large capital investments.

2.2 Embedded Systems and Control Technologies

Control systems for robotic arms can range from simple microcontroller-based PWM control to complex AI-driven machine learning algorithms. In literature, Arduino and Raspberry Pi platforms have dominated beginner and academic-level projects due to their ease of use and extensive community support. However, they present limitations in processing power or connectivity.

In contrast, the ESP32 microcontroller offers a perfect blend of performance, connectivity, and cost. With dual-core processing, built-in Wi-Fi and Bluetooth, and low-power consumption, ESP32 has emerged as a go-to choice for many robotics and IoT applications. .

Several recent projects in open-source communities have showcased ESP32-based robotic systems for home automation, surveillance, and educational kits. Most notably, ESP32 has been used in wireless remote-controlled robotic cars, bionic arms, and Wi-Fi-enabled sensor networks. These projects highlight the versatility and reliability of ESP32 as a wireless controller for robotic systems.

2.3 Mechanical Design and CAD Modeling

Robotic arms require robust mechanical design to ensure fluid motion and adequate load handling. Literature emphasizes the use of CAD tools like SolidWorks, Fusion 360, and AutoCAD for the design and simulation of robotic joints and linkages. Studies have shown that CAD simulations help significantly reduce design flaws and allow for stress testing before physical fabrication. Components such as servo horns, joint brackets, base mounts, and gripper mechanisms can be custom-designed and either 3D printed or CNC machined.

Projects like the "Thor" open-source 3D printable robotic arm and "uArm" desktop robot showcase how detailed mechanical design contributes to both aesthetics and functionality. These designs often use modular joints that can be easily upgraded or replaced, a principle also adopted in the XIMO arm.

2.4 PCB Design in Robotics

One often overlooked but crucial component in robotic arm design is the custom PCB. Most hobby projects rely on breadboards or pre-assembled modules, which are prone to loose connections, signal noise, and power issues. Literature from embedded electronics development highlights the advantages of custom PCBs, including:

Cleaner layout and compact design.

Dedicated power rails for high-current components (e.g., servo motors).

Integration of headers for microcontrollers, sensors, and displays.

Improved signal integrity and durability.

In academic and commercial case studies, PCB-based controller designs have been linked to greater system reliability and production scalability. Tools like Altium Designer, KiCad, and Eagle are widely referenced in PCB design literature, offering schematic-to-layout workflows with simulation and manufacturing export options.

For XIMO, the adoption of Altium Designer for transmitter and receiver PCB design aligns with best practices in professional embedded development. This approach allows for proper component placement, thermal consideration, and modular expandability.

2.5 Feedback Systems and Displays

OLED displays and feedback sensors play a vital role in providing system transparency and real-time diagnostics. Numerous research papers discuss the benefits of including I2C-based OLEDs in robotic systems to display operational states, errors, and telemetry data. These interfaces are lightweight, power-efficient, and easy to integrate using libraries available for ESP32 and Arduino platforms.

In higher-end systems, feedback mechanisms such as rotary encoders, limit switches, and force sensors provide precision and prevent mechanical failure. Although not implemented in the current version of XIMO, these are widely referenced in literature as the next step for improving closed-loop control and real-time error correction.

2.6 Gaps and Contribution

While many open-source robotic arm projects exist, very few offer a balanced integration of:

Professional CAD design

Custom PCB electronics

Real-time wireless control

Feedback display integration

XIMO stands out by combining these features into a single, cost-effective prototype. Its documentation, modular design, and use of industry-standard tools make it replicable and scalable for educational and research purposes.

3.METHODOLOGY

The successful development of XIMO – An Industrial Robotic Arm required an interdisciplinary approach involving mechanical design, embedded system integration, wireless communication, and hardware fabrication. The methodology adopted for this project focused on achieving reliability, modularity, and efficiency in both mechanical and electronic subsystems. The system was divided into four key phases: architecture planning, hardware selection and integration, software development, and final implementation.

3.1 System Architecture

The architecture of XIMO was planned with a modular, distributed control system in mind. The robotic arm is wirelessly operated via two ESP32 microcontrollers—one functioning as the transmitter and the other as the receiver. The transmitter is responsible for reading input commands from the user (e.g., via buttons or a joystick) and sending these commands wirelessly to the receiver using the ESP-NOW communication protocol. The receiver interprets the commands and actuates four servo motors, each responsible for one degree of freedom in the arm: base rotation, shoulder lift, elbow movement, and gripper control.

A key component in the transmitter module is a 0.96” OLED display, which provides real-time feedback to the user about the system’s status, such as connectivity, command transmission, and active modes. The receiver module is mounted directly on the robotic arm and manages the execution of commands by generating precise PWM signals for each servo motor.

This modular architecture ensures:

Reduced wiring and cleaner assembly through custom-designed PCBs

Scalability for future features like feedback sensors or additional DOFs.

Independent testing and debugging of TX and RX modules.

3.2 Hardware Components

3.2.1 Microcontrollers – ESP32 (x2)

Two ESP32 modules were used due to their dual-core architecture, low power consumption, integrated Wi-Fi/Bluetooth, and support for custom wireless protocols like ESP-NOW. This enabled low-latency communication and sufficient processing power for both signal transmission and PWM generation.

3.2.2 Servo Motors (x4)

Standard servo motors such as SG90 or MG996R were used depending on the torque requirements of each joint. These motors provide precise angular control based on the PWM signals and are cost-effective for small-scale robotic applications.

3.2.3 OLED Display

An SSD1306-based 0.96” OLED screen is mounted on the transmitter unit. It communicates over I2C and displays user-friendly messages such as “Connected,” “Disconnected,” or “Command Sent,” improving interactivity and system transparency.

3.2.4 Custom PCBs

Both the transmitter and receiver units were integrated into compact PCBs designed in Altium Designer. These PCBs include:

ESP32 headers

4–6 pin servo headers

Power input and regulation circuitry

I2C interface for OLED

Capacitors and regulators for noise suppression

3.2.5 Mechanical Structure

The mechanical framework of the robotic arm was designed using SolidWorks. It consists of multiple joints and links designed to support each DOF. The body is fabricated from lightweight material suitable for prototyping, such as acrylic or 3D-printed PLA. The structure was optimized for stability and motor load balance.

3.2.6 Power Supply

Servo motors are powered using an external 5V/3A regulated power supply. Voltage regulators (AMS1117 or LM7805) are included on the PCB to power the ESP32 units safely. A decoupled power architecture ensures stable operation and prevents brownouts during simultaneous motor movements.

3.3 Software Tools and Technologies

The development workflow incorporated a mix of design, simulation, and programming tools:

Arduino IDE: Used for writing and uploading code to the ESP32 modules. C++ was the primary language.

ESP-NOW: Used for peer-to-peer communication between TX and RX modules. It allows packet-based, low-latency wireless data transfer without Wi-Fi pairing.

U8g2 Library: An open-source library for controlling the OLED display via I2C.

SolidWorks: Used for 3D CAD modeling, simulation, and kinematic testing of the robotic arm structure.

Altium Designer: Used for schematic creation, PCB layout, and generating fabrication-ready Gerber files.

3.4 Implementation Details

3.4.1 Mechanical Design & Fabrication

Using SolidWorks, the robotic arm was modeled with precision to simulate movement, joint constraints, and motor placement. The parts were designed to be compatible with commonly available servo motors. Once modeled, the parts were exported as STL files and fabricated using 3D printing (for prototypes) or laser-cut acrylic (for stronger, lighter arms).

3.4.2 PCB Design & Fabrication

In Altium Designer, circuit schematics for both transmitter and receiver units were created. The boards were laid out with optimal routing to separate power and logic paths, ensuring reduced electrical noise. Power filtering capacitors were included to handle voltage spikes from servo motors. The PCBs were fabricated and tested before full integration.

3.4.3 Firmware Development

ESP32 firmware was developed using the Arduino IDE. The transmitter reads button/joystick inputs, packages them as ESP-NOW data packets, and transmits them to the paired receiver. The receiver decodes the data and drives the appropriate PWM signals to the servo motors. Debouncing techniques and watchdog timers were used to ensure stable control.

3.4.4 Integration & Testing

Once individual modules were tested, the full system was assembled and tested for:

Wireless range (up to 15 meters in open environments)

Servo responsiveness and delay

Power stability under full motor load

OLED readability in different lighting conditions

This structured methodology ensured a reliable, modular, and scalable robotic system. XIMO’s architecture also allows for future enhancement such as adding feedback sensors, increasing DOFs, or integrating with IoT/cloud systems for real-time remote monitoring.

4.Embedded System Implementation

The embedded system in *XIMO – An Industrial Robotic Arm* plays a critical role in enabling real-time wireless communication, motor control, and feedback mechanisms. The system is designed to be power-efficient, low-latency, and modular, integrating both hardware and firmware seamlessly. This section outlines the key steps and design decisions made in selecting components, designing circuits, creating PCBs, and programming the microcontroller units.

4.1 Microcontroller/Processor Selection

The heart of XIMO's electronic control system is the **ESP32 microcontroller**, selected based on the following key criteria:

Why ESP32?

- **Dual-core 32-bit processor** (Xtensa LX6 architecture), clocked up to 240 MHz.
- **Built-in Wi-Fi and Bluetooth** capabilities.
- **Support for ESP-NOW**, a low-power, peer-to-peer communication protocol.
- **Up to 16 PWM outputs**, ideal for multi-servo applications.
- Low cost, compact size, and widely supported in the Arduino ecosystem.

The choice of ESP32 allowed the team to achieve low-latency wireless control without relying on traditional Wi-Fi network infrastructure or Bluetooth pairing, both of which could introduce unwanted delays or dependencies.

4.2 Circuit Design

The control system circuitry was divided into two separate but complementary circuits: the **transmitter unit** and the **receiver unit**.

Transmitter Unit

- **Inputs**: Buttons, joystick, or other control interfaces.
- **ESP32**: Reads inputs and sends packets using ESP-NOW.
- **OLED Display (0.96” SSD1306)**: Connected via I2C to show system status.
- **Voltage Regulator**: Ensures stable 3.3V for ESP32 from a 5V source.

Receiver Unit

- **ESP32**: Receives wireless packets, processes them, and outputs PWM signals.
- **Servo Connectors (4)**: Each connected to one of the robotic arm’s joints.
- **Power Distribution**: Separate 5V power line for servo motors to prevent interference with logic-level components.

- **Decoupling Capacitors**: Added to stabilize voltage supply during high-current servo movement.

Both circuits were first prototyped on a breadboard to test functionality and then converted into PCBs for reliability and compactness.

4.3 PCB Layout

To improve the reliability and professional presentation of the system, custom PCBs for both the transmitter and receiver were designed using **Altium Designer**, a powerful PCB design software used in industry.

Design Considerations

- **Compact Size**: Boards were optimized for minimum footprint while keeping access to all necessary GPIOs.
- **Clear Routing**: Power, ground, and signal lines were separated and shielded to reduce noise.
- **Servo Headers**: 3-pin headers were used for each servo for easy plug-and-play.
- **I2C Headers**: For connecting OLED or other future I2C-based peripherals.
- **Mounting Holes**: Included for enclosure and arm attachment.

PCB Designing

- Made a Home-made PCB.
- Making a rviz implantation.

4.4 Firmware Development

The embedded code for both ESP32 units was developed using **Arduino IDE** with C++.

Transmitter Firmware

- Reads inputs from buttons/joystick.
- Encodes servo commands into structured ESP-NOW packets.
- Sends packets to the receiver at fixed intervals (~20ms).
- Uses **U8g2 library** to display messages like:
  - "Connected"
  - "Sending Command"
  - "Signal Lost"

Receiver Firmware

- Registers to listen for ESP-NOW messages.
- Decodes the command structure.
- Maps incoming values to PWM angles (0–180°) using ESP32's hardware timers.

- Outputs PWM signals to servo headers.
- Includes fail-safes in case of communication timeout or corrupted data.

Features Added

- **Watchdog timers**: Reset system in case of code freeze.
- **Failover logic**: Maintain last known safe state if no new command is received.
- **Modular functions**: Code split into reusable modules for motor control, communication, and display.

System Performance

- **Wireless Range**: Stable control observed up to 12–15 meters in open space.
- **Latency**: ~15ms round-trip, fast enough for real-time control.
- **Servo Accuracy**: ±2° error margin under no load.
- **Power Efficiency**: Operates for ~2–3 hours on a 2000mAh battery for demonstration purposes.

This embedded system implementation demonstrates how careful hardware selection, circuit design, and modular firmware development can lead to a responsive, reliable, and user-friendly robotic control system. XIMO's architecture is not only effective but also scalable for future applications involving feedback systems, autonomous motion, and AI integration.

5.Results and Discussion

The *XIMO* project was designed and developed as a 5-Degree-of-Freedom (DOF) wireless-controlled robotic arm intended for industrial automation tasks such as object manipulation and pick-and-place operations. Once the system was fully integrated—combining mechanical assembly, custom PCBs, ESP32-based control, and firmware—the prototype underwent multiple rounds of testing under lab conditions. This section presents an analysis of the results, a comparison with existing systems, and a reflection on the benefits and limitations of the current implementation.

5.1 Performance Analysis

The performance of XIMO was evaluated based on several key parameters, including **wireless communication stability**, **servo response accuracy**, **mechanical precision**, **system latency**, **range**, and **power efficiency**.

5.1.1 Wireless Communication and Latency

XIMO uses **ESP-NOW**, a peer-to-peer wireless communication protocol supported by the ESP32. Unlike traditional Wi-Fi or Bluetooth protocols, ESP-NOW requires no internet connectivity or device pairing, offering near-instantaneous packet transmission.

- **Transmission delay:** ~10–15 ms average, even at full range.
- **Effective range:** 10–15 meters in open space without packet loss.
- **Packet success rate:** Over 98% across 1000+ test transmissions.

This demonstrated excellent communication reliability, which is critical for real-time robotic control.

5.1.2 Servo Motor Accuracy

Servo movement was tested by sending predefined angle commands and measuring the actual output angle using a protractor and camera analysis. The system maintained:

- **Angle deviation:** ±2° under no-load conditions.
- **Speed response time:** 200–400 ms for full-angle sweep.
- **Consistency:** No skipped signals or jitter observed under nominal voltage.

Each joint performed smoothly and with repeatability, confirming the effectiveness of the PWM signal generation on the ESP32.

5.1.3 Mechanical Robustness

The CAD-designed mechanical components fabricated using PLA (3D printed) or acrylic sheets showed good durability during repeated movement. Fasteners and servo placements remained tight, with no mechanical backlash after 100+ operation cycles.

5.1.4 OLED Feedback and User Interface

The OLED display on the transmitter functioned accurately, displaying key information such as:

- Signal status (Connected/Disconnected)
- Current command being sent
- Battery or power input status (optional feature)

This provided transparency during operation and made system testing more intuitive.

5.1.5 Power Efficiency

Using a regulated 5V/3A adapter, the entire system ran efficiently. Peak current draw occurred during simultaneous servo movements but remained within safe operational margins. The separate power lines for logic (ESP32) and servos prevented brownouts or resets, enhancing system stability.

5.2 Comparisons with Existing Systems

XIMO was compared with common alternatives such as **Arduino-based robotic arms**, **Bluetooth-controlled kits**, and open-source systems like **uArm** or **Thor**.

Feature	**XIMO**	**Arduino Kits**	**Bluetooth Arms**	**uArm/Thor**
Wireless Protocol	ESP-NOW (Low-latency)	Optional	Bluetooth (Slower)	USB / Network
Servo Control	ESP32 PWM (Hardware-level)	Software PWM (Less precise)	Moderate	High precision
Feedback System	OLED Display	No display	Optional app	GUI-based feedback
PCB Integration	Custom-designed	Breadboard/module-based	Module-based	PCB-ready
Cost	Low	Moderate	Low	High
Scalability	High	Limited	Limited	High
Open-source	Yes	Yes	Partially	Yes

From this comparison, it's evident that XIMO offers:

- **Better wireless responsiveness than Bluetooth-controlled models**
- **More polished and compact hardware via PCB integration**
- **Greater transparency through onboard feedback**

Although it doesn't yet match high-end features like sensor feedback or precision of industrial-grade arms, XIMO presents a strong balance between cost, performance, and modularity.

5.3 Advantages and Limitations

5.3.1 Advantages

1. **Low-Cost and Open Source:** Utilizes inexpensive ESP32 modules and servo motors, making it accessible for students, hobbyists, and SMEs.
2. **Modular Design:** The architecture allows each module (TX, RX, mechanical arm) to be upgraded or replaced independently.
3. **Custom PCBs:** Clean, professional-grade design reduces wiring complexity and increases robustness.
4. **Wireless Control:** ESP-NOW eliminates dependency on Wi-Fi or Bluetooth infrastructure.
5. **User Feedback:** OLED display improves usability and debugging during development and operation.
6. **Lightweight and Portable:** The mechanical structure is compact and suitable for table-top use.

Conclusion of Results

XIMO successfully meets its goal of being a low-cost, modular, and wirelessly controlled industrial robotic arm. It offers excellent performance in communication, mechanical stability, and servo precision for its class. While not a replacement for full-fledged industrial robots, it serves as a powerful educational and prototyping platform, and a solid foundation for integrating advanced features like AI, vision systems, and feedback control in future iterations.