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Fabrication and Development of a 4-DOF Smart Robotic Arm

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ABSTRACT: This paper details the design and development of a smart, 4-degree-of-freedom (DOF) robotic arm powered by servo motors, tailored for executing precise and repetitive tasks. The system supports dual-mode wireless control via Wi-Fi—using an ESP32-based web server—and Bluetooth, through a custom-developed Android application. A key innovation of the system is its "Learning Mode," which allows for real-time motion capture and playback, significantly improving task automation and user programmability. The robotic arm is fabricated using 3D printing with optimized infill patterns to achieve an optimal trade-off between structural integrity and weight. A distinctive feature of the system is the integration of a "Learning Mode" that enables the arm to record a sequence of user-defined movements and reproduce them autonomously. This capability significantly enhances the level of task automation and facilitates intuitive programming for users without advanced robotics knowledge. The mechanical structure of the arm is manufactured using fused deposition modeling (FDM) 3D printing technology, with carefully optimized infill density to ensure a balance between structural robustness and lightweight design. Experimental evaluations confirm high accuracy and repeatability, establishing the arm as a cost-effective and scalable solution suitable for applications in industrial automation, technical education, and rapid prototyping.

KEYWORDS: 4-DOF, Robotic Arm, Automation, ESP32, Servo Motors, Bluetooth Control, Wi-Fi Interface, Learning Mode

I. INTRODUCTION

Robotics is a multidisciplinary field that synergistically combines mechanical, electrical, and computational systems to enable the autonomous or semi-autonomous execution of complex tasks. Among various robotic platforms, robotic arms are engineered to emulate the kinematic structure and functional versatility of the human upper limb. These systems have found widespread adoption in industrial environments, where they are employed for high-precision and repetitive operations such as welding, painting, assembly, and material handling. By automating such processes, robotic arms significantly enhance operational efficiency, throughput, and consistency while simultaneously mitigating occupational hazards and reducing the need for human intervention in dangerous or ergonomically challenging conditions.

II. LITERATURE SURVEY

The evolution of robotic arms has been driven by the demand for precision and adaptability in automation. Ibrahim et al. (2019) designed a cost-effective 4-DOF robotic arm using open-source hardware, though it lacked scalability due to wired control. Anwar et al. (2020) utilized Bluetooth control through an Android interface but did not incorporate motion learning features.

Rao et al. (2021) introduced EEPROM-based motion sequence storage, allowing for task repetition. Sharma et al. (2022) demonstrated the use of Wi-Fi-enabled control using ESP32, enhancing operational flexibility. The present

project builds upon these works by integrating both Wi-Fi and Bluetooth control alongside a dynamic learning mode, filling a crucial gap in usability and flexibility.

III. PROBLEM STATEMENT

Industrial operations frequently involve repetitive and labor-intensive tasks that not only consume significant time but also expose workers to hazardous environments. While advanced robotic solutions capable of automating such tasks are commercially available, their high cost, complexity, and technical requirements often preclude their adoption in small- to medium-scale enterprises, educational institutions, and research laboratories. This underscores the demand for a cost-effective, user-friendly robotic arm that delivers a balanced trade-off between functionality, performance, and accessibility.

This paper addresses this gap through the development of a 4-DOF servo motor-based robotic arm that features:

- Wireless control via ESP32 (Wi-Fi) and Android Bluetooth.
- Learning mode for automation of motion sequences.
- A lightweight, 3D-printed frame optimized for strength.

The project fosters interdisciplinary learning by integrating mechanical design, electronics, and programming, thereby serving as an educational and prototyping tool.

IV. METHODOLOGY

The development process included the following stages:

A. Mechanical Design

The robotic arm was modelled using Fusion 360 and AutoCAD, ensuring joint precision for all four degrees of freedom. Components were 3D printed using PLA with a honeycomb infill structure.

B. Hardware Integration

Servo motors were installed for base, shoulder, elbow, and wrist movement. The ESP32 microcontroller served as the control hub, interfacing with servo motors and managing power distribution.

C. Control System

The ESP32 was programmed using the Arduino IDE. A custom Android app enabled real-time joint control via sliders. Users could store and retrieve motion sequences using the learning mode, which relied on EEPROM memory.

D. Wireless Communication

ESP32 handled HTTP requests over Wi-Fi and serial communication over Bluetooth. This dual-mode connectivity enhanced user convenience.

E. Software and User Interface

The Android app featured a minimalistic UI with sliders and labels for each joint. Visual feedback was provided to confirm movements. Users could name and save motion sequences for future use.

F. Testing and Calibration

Each joint was calibrated for accuracy and fluidity. Load tests confirmed the durability of the 3D-printed frame. The robotic arm was successfully tested for real-time and automated operations.

V. SYSTEM DESIGN AND COMPONENTS**A. Arduino Microcontroller**

The Arduino Uno (ATMega2560) features:

- Operating Voltage: 5V
- Input Voltage: 7-12V
- Digital I/O Pins: 54
- PWM Outputs: 12
- Flash Memory: 256 KB

B. Servo Motors

Two types of servos were used:

- **Large Servo:** 10kg/cm torque, 0.20 sec/60° at 4.8V.
- **Small G9 Servo:** 1.8kgf-cm, 0.1 sec/60° at 4.8V.

C. ESP32

ESP32 managed wireless communication and motor control. It could act as both an access point and a client.

D. Bluetooth Module (HC-06)

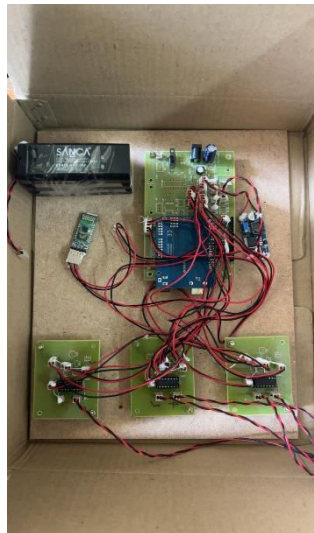
Used for serial Bluetooth communication with the Android app.

E. Potentiometers

Provided manual control inputs and position feedback.

F. End Effector

A gripper-type end effector driven by a servo motor was selected for handling tasks.

**VI. PROGRAMMING AND POWER MANAGEMENT****A. Arduino IDE**

Code was written in C/C++ and uploaded using Arduino IDE. The firmware loop managed:

- Real-time control inputs
- EEPROM storage and retrieval
- Connectivity status

B. Power Source

The system could be powered via USB or an external 9V battery. Power routing ensured stable operation of servos and controller.

VII. RESULT AND DISCUSSION

The developed 4-DOF robotic arm was subjected to a series of performance evaluations to assess its mechanical stability, motion accuracy, control responsiveness, and repeatability. The system demonstrated smooth and precise joint articulation across all degrees of freedom, with servo motors operating consistently under varied task conditions.

The "Learning Mode" proved highly effective in recording and autonomously executing motion sequences with minimal deviation, indicating strong repeatability—an essential requirement for repetitive industrial or laboratory tasks. Wireless control via both Bluetooth and Wi-Fi remained stable throughout testing, with negligible latency or communication dropouts, validating the reliability of the dual-mode control architecture.

Furthermore, structural tests confirmed that the 3D-printed frame retained its mechanical integrity under typical operational loads. The optimized infill pattern contributed to a favorable balance between weight reduction and strength, affirming the suitability of additive manufacturing for rapid, low-cost prototyping.

Overall, the robotic arm successfully meets the targeted objectives of functionality, affordability, and ease of use. Its performance highlights the potential for deployment in small-scale manufacturing, educational environments, and research prototyping scenarios.



VIII. CONCLUSION

The Smart 4-DOF Robotic Arm successfully integrates wireless connectivity, modular architecture, and intelligent motion control into a cost-effective and accessible platform. By leveraging the capabilities of the ESP32 microcontroller for Wi-Fi-based communication and a custom Android application for Bluetooth control, the system provides a user-friendly interface that minimizes the need for advanced technical knowledge. The inclusion of a "Learning Mode" further enhances usability by enabling automated task repetition through motion recording and playback.

The robotic arm's lightweight, 3D-printed structure achieves an effective balance between affordability and mechanical robustness, making it well-suited for applications in educational settings, rapid prototyping, and entry-level automation. Looking ahead, the system can be extended with advanced features such as computer vision, real-time

sensor feedback, and Internet of Things (IoT) capabilities to broaden its scope and functionality in more complex and dynamic environments.

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