Development of a Six-Degree-of-Freedom Robotic Arm Based on Teach–Playback Motion Control

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Abstract - In the present work, a six-DOF robotic arm for automated pick-and-place tasks is introduced. The suggested system uses a teach-playback model in which the user manually directs the robotic arm through a predetermined set of movements. Without the assistance of external sensors, these motions are recorded and then automatically repeated. The robotic arm performs tasks according to predetermined joint angle trajectories, producing precise and repeatable movements in regulated settings. The design's emphasis on affordability, adaptability, and simplicity makes it appropriate for small-scale automation systems, lab experimentation, and educational institutions. Without sensor-based input, the system is less complex while still performing well enough for prescribed tasks. The proposed robotic arm exhibits dependable performance for applications that do not demand real-time environmental adaptation.

Key Words: *Six Degrees of Freedom (6-DOF), Robotic Arm, Pick and Place Automated System, Joint Orientation Control, Teach-playback control, Sensor less Operation and Educational Robotics*

1. INTRODUCTION

Traditional industrial robotic systems frequently include sophisticated control algorithms and intricate sensor networks, which raises the cost and complexity of the system's design. In applications including material handling, assembly, and pick-and-place tasks, robotic arms have emerged as a crucial aspect of contemporary automation systems. Such intricacy is sometimes superfluous for small-scale automation and educational settings.

This work describes the design and implementation of a teach-playback control strategy for a six-DOF robotic arm. This approach involves manually guiding the robot through a series of predetermined movements that are captured and saved in memory. Without the use of external sensors or real-time feedback systems, the motion data that has been saved is subsequently replayed to carry out tasks on its own.

The proposed robotic arm performs consistently and precisely in controlled conditions by following predetermined joint trajectories. The system is suitable for training, small-scale automation tasks, and academic labs because it has been created with simplicity, adaptability, and cost effectiveness in mind. The primary objective of this work is to show that, under well-defined operating conditions, reliable robotic manipulation can be accomplished without significant sensing.

2. PROPOSED SYSTEM

In the proposed system, a six-DOF robotic arm designed to carry out automatic pick-and-place tasks using a teach-playback control mechanism is shown alongside its implementation. Without the use of external sensors or intricate feedback control, the system is designed to function in controlled environments where repetitive activities can be completed.

The system's general architecture includes a motor driving stage, a wireless communication module, a microcontroller-based control unit, a mechanical robotic arm assembly, and a motion input user interface. The controller receives user-defined motion commands wirelessly, allowing the robotic arm to be operated remotely and flexibly. In order to drive the actuators, the control unit interprets the commands it has received and produces the proper control signals.

The ESP32 microcontroller is used as the central processing unit because of its effective real-time control performance and built-in Bluetooth connectivity capability. Accurate control signals for the servo motors are produced by a specialized PWM driver, ensuring coordinated joint movement. During operation, the robotic arm can accomplish exact positioning and orientation by virtue of the one degree of freedom that each servo motor represents.

The mechanical layout and joint dimensions were first designed in Blender, allowing accurate visualization of link geometry before physical assembly. This process guarantees dependable mechanical alignment and seamless wireless operation in a small, inexpensive robotic platform.

The proposed method prioritizes cost-effectiveness, simplicity, and modularity. The robotic arm offers dependable and repeatable motion appropriate for training platforms, educational labs, and small-scale automation applications by using wireless command transmission and predetermined joint trajectories. The block diagram in Figure 1 depicts the overall system configuration.

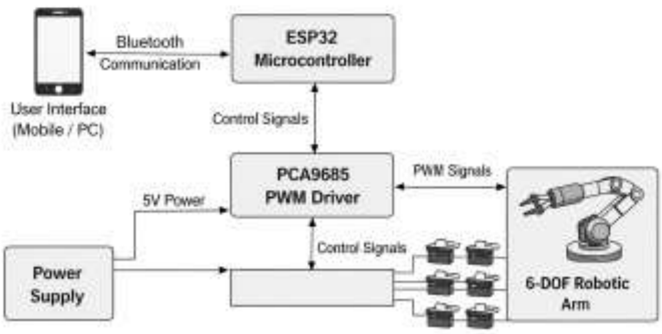

Fig. 1 Block Diagram of the Proposed 6-DOF Robotic Arm System

2.1 Block Diagram Explanation

The block diagram of the proposed six degrees of freedom (6-DOF) robotic arm system illustrates the overall functional architecture and interaction between different system components, as shown in Figure 1. The system uses a teach-playback control mechanism with wireless command transmission to carry out automated pick-and-place tasks.

The input unit is the user interface, where motion commands are produced via a control device or a mobile application. Bluetooth connectivity is used to send these commands wirelessly to the control device. Without physical ties, wireless networking enables the robotic arm to operate remotely and flexibly.

The ESP32 microcontroller, which controls Bluetooth connectivity and decodes incoming user commands, is the central component of the control system. The PCA9685 PWM driver receives these directives over the I²C interface after they have been translated into joint angles. The six MG90S servos in charge of each degree of freedom are driven by precise 50 Hz PWM signals produced by the PCA9685. Stable multi-axis control is ensured by this separation of processing and actuation, which also minimizes the computational load on the ESP32 minimal. Each servo undergoes a calibration routine to establish zero positions and enforce safe operating limits. A smooth interpolation mechanism is used to transition between target angles, preventing sudden movements that could damage the arm. Safety features such as speed limiting and angle clipping ensure reliable performance even during rapid control inputs. Bluetooth timing and servo response were iteratively refined for consistent and precise operation across all six joints.

An external power supply provides the required electrical power to the controller and actuators, ensuring stable system operation.

All things considered, the block diagram shows a small and effective system architecture that combines accurate motor actuation, wireless control, and a well-organized mechanical design to produce dependable and repeatable robotic arm operation.

3. METHODOLOGY

System design, control strategy, hardware implementation, software development, and experimental validation comprise the process used to construct the suggested six-DOF robotic arm. The goal is to use a teach-playback control mechanism with wireless communication to accomplish dependable pick-and-place operation.

3.1 System Design

The overall system architecture consists of a user interface, wireless communication module, control unit, motor driving stage, and a mechanical robotic arm assembly. Motion commands are provided by the user and transmitted wirelessly to the control unit. The system architecture is designed to ensure modularity, ease of implementation, and low cost while maintaining reliable operation.

3.2 Mechanical Design

The robotic arm is designed with six independently actuated rotational joints to provide flexible positioning and orientation of the end-effector. The mechanical structure and joint dimensions are modeled using Blender software to verify link alignment and range of motion prior to physical assembly. A gripper is mounted at the end-effector to perform grasping and releasing actions during pick-and-place tasks.

3.3 Control Strategy (Teach–Playback Mechanism)

The control methodology is based on two operating modes: teaching mode and playback mode. In teaching mode, the user manually guides the robotic arm through the desired motion sequence. During this process, joint angle values corresponding to each servo motor are recorded and stored in the controller memory. In playback mode, the stored joint trajectories are retrieved and executed sequentially, allowing the robotic arm to reproduce the demonstrated motion accurately without the use of external sensors.

3.4 Hardware Implementation

An ESP32 microcontroller is used as the central control unit due to its integrated Bluetooth capability and efficient processing performance. Wireless motion commands received via Bluetooth are converted into joint angle values. A PCA9685 PWM driver is employed to generate precise control signals for six MG90S servo motors, with each servo controlling one degree of freedom. An external power supply is used to provide sufficient current to the servo motors and control circuitry.

3.5 Software Development

The 6-DOF robotic arm was developed using integrated software tools for wireless control, mechanical design, and programming. Using the Arduino IDE, embedded C/C++ programs were created and uploaded to the microcontroller, allowing for real-time system monitoring and servo control via serial communication. Blender 5.0.0 was used for mechanical design in order to precisely measure the structural parts of the robotic arm, check for alignment and articulation, and generate STL files for 3D printing. The Bluetooth Electronics application, which connects to the microcontroller using a Bluetooth module and sends real-time joint control commands via a configurable smartphone interface, was used to accomplish wireless operation. When used in tandem, these instruments guaranteed the robotic arm system's effective design, manufacturing, and seamless real-time operation.

3.6 Experimental Procedure

The performance of the robotic arm is evaluated through pick-and-place experiments conducted in a controlled environment. The completed system underwent testing for repeatability, stability, and responsiveness in a range of operating scenarios. To accomplish smooth real-time motion, PWM ranges, joint offsets, and communication latency were adjusted. Low-delay control and dependable communication were confirmed for the Bluetooth interface. All things considered, the optimized configuration facilitates teach-playback execution, coordinated multi-DOF movement, and reliable performance appropriate for robotic applications at the prototype level.

3.7 Hardware Description

The hardware components used in the development of the proposed six degrees of freedom (6-DOF) robotic arm are selected to achieve reliable performance while maintaining low cost and simplicity.

The proposed 6-DOF robotic arm's hardware architecture is made to guarantee accurate motion control, reliable power management, and effective system integration. High-torque servo motors for joint actuation, a regulated power supply, a specialized servo driver module for multi-channel PWM generation, a microcontroller-based control unit, and a specially designed 3D-printed mechanical structure are all included. Together, these parts enable the robotic arm to articulate smoothly and operate dependably in real time. The key hardware components and their specifications are summarized in Table 1.

S.No	Component	Key Specifications
1	ESP32 Microcontroller	32-bit dual-core processor, 240 MHz, integrated Wi-Fi & Bluetooth, 3.3V logic
2	PCA9685 Servo Driver	16-channel PWM controller, 12-bit resolution, I2C interface, 5V supply
3	MG90S Servo Motor	Operating voltage: 4.8–6V, Torque: ~2.2 kg·cm, Metal gears, 0–180° rotation
4	Power Supply	Output: 5V DC, Current ≥3A regulated supply
5	3D Printed Arm Structure	Material: PLA/ABS, Lightweight design, Custom STL-based fabrication
6	B-Type Cable & Connecting Wires	USB Type-B for programming, Jumper wires for signal and power connections

Table 1: Hardware Components and Specifications of the Proposed 6-DOF Robotic Arm

4. RESULT and DISCUSSION

The 6 DOF robotic arm was successfully designed, 3D printed, assembled, and tested, demonstrating stable mechanical performance across all six joints. Each MG90S servo motor responded accurately to the commanded angles, enabling smooth articulation of the base, shoulder, elbow, wrist pitch, wrist roll, and gripper. The integration of the ESP32 with the PCA9685 driver ensured precise PWM control, even during simultaneous multi axis movements. Bluetooth communication enabled real time wireless operation, allowing the arm to be controlled effortlessly through a mobile or PC interface without any physical tethering. The teach–playback mechanism functioned reliably, capturing user guided motions and reproducing them with consistent accuracy.

The system successfully carried out colour-based sorting by identifying the colours of the objects and initiating the matching motion sequences that had been previously learned.

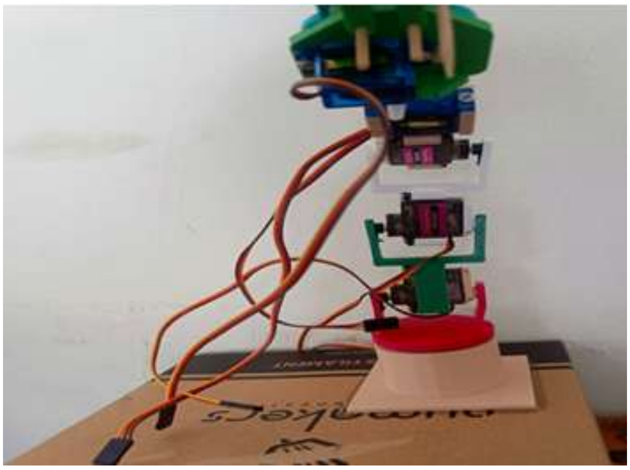

Fig -2: 6-Degrees of Freedom Robotic Arm

Throughout several cycles, the arm's performance remained steady, exhibiting no discernible servo jitter or drift. The 3D printed pieces' precise mechanical alignment allowed for smooth rotation and little backlash. Without ESP32 resets or voltage drops, continuous functioning was guaranteed by power delivery from the regulated 5V supply.

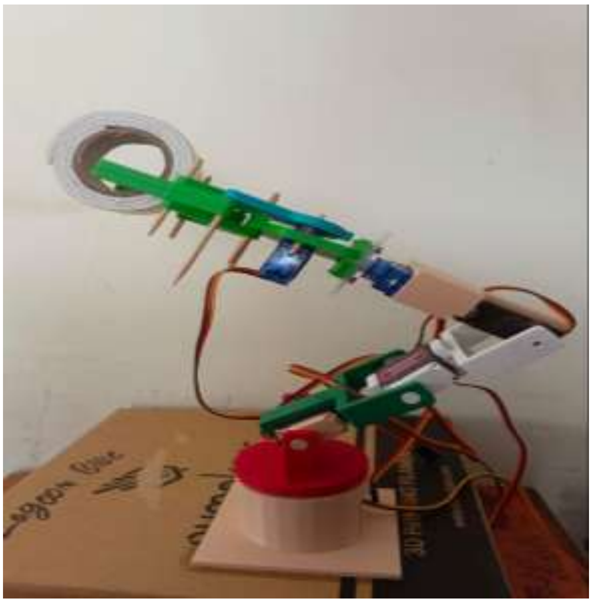

Fig -3: 6-DOF robotic arm output

Overall, the completed system achieved accurate motion reproduction, dependable wireless control, and functional automation capabilities appropriate for light industrial and educational presentations, validating the design goals.

5. CONCLUSIONS

For automated pick and place tasks, the 6 DOF robotic arm project offers a small, affordable, and retrainable solution. The system combines Bluetooth connectivity, ESP32 microcontroller, PCA9685 driver, and MG90S servo motors to provide wireless control and smooth multi-axis motion. The teach-playback technology eliminates the need for manual reprogramming by enabling dependable motion replication based on colour identification and easy teaching. The modular design facilitates simple assembly and modification, while the 3D printed structure provides lightweight rigidity. Debugging and performance validation are improved with real-time feedback via Bluetooth serial monitoring. All things considered, the system fulfills its design objectives and works effectively in situations involving instruction, demonstration, and mild automation.
The developed robotic arm is especially well suited for training platforms, educational labs, and small-scale automation jobs where affordability and ease of use are crucial. The work demonstrates that, under carefully controlled operating conditions, a sensorless teach-playback approach can be used to accomplish efficient robotic manipulation.

6. FUTURE SCOPE

The future development of the system includes integrating advanced sensors such as force sensors, encoders, and vision modules to enhance precision and adaptive control. AI-powered motion planning can enhance object detection and sorting effectiveness while further optimizing trajectories. With its user-friendly controls and real-time feedback, a mobile application interface helps streamline operations. Academic teaching and virtual testing will be made possible by integration with simulation systems such as Gazebo or RViz. Furthermore, collaborative robotics features enable interaction with humans or other robots, and battery-powered operation can facilitate portability. Additionally, the platform can be a useful testbed for studies in modular robotics, sensor fusion, and control algorithms.

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