Voice and Remote Control Object Detection Robotic Arm:A Review Paper

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Abstract

This extensive research paper details the end-to-end development of a 4-Degree of Freedom (4-DOF) robotic arm. The system serves as a benchmark for low-latency human-robot interaction by utilizing the ESP32's dual-core processor. The primary control system utilizes a manual potentiometric bridge (10k ohms), while the secondary system implements high-fidelity voice recognition via the INMP441 I2S digital microphone. This study explores the mechanical stress analysis of the acrylic frame, the mathematical modeling of forward kinematics, and the electrical stabilization strategies on a Zero-PCB layout. The results demonstrate that the proposed architecture minimizes electromagnetic interference (EMI) and provides a highly granular control resolution of 4096 steps, significantly outperforming legacy 8-bit systems.

Keywords

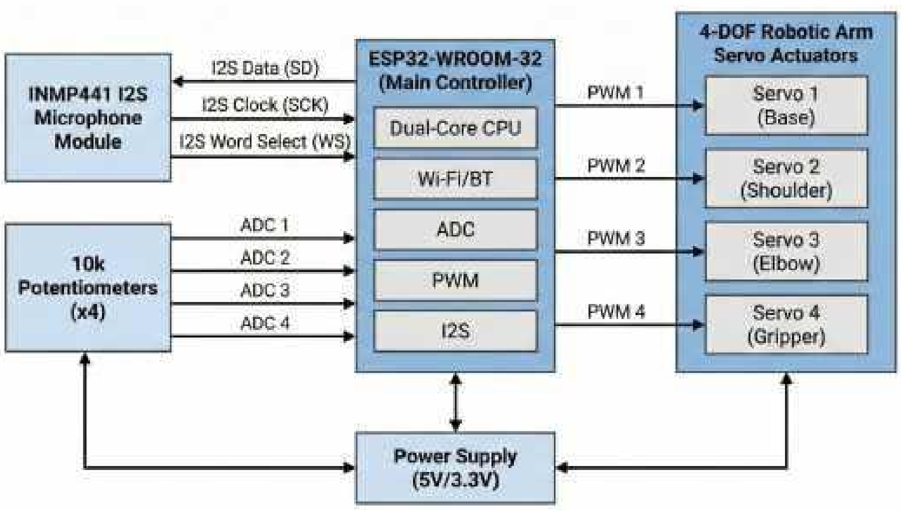
ESP32, 4-DOF Robotics, INMP441, I2S Digital Audio, PWM Signal Stability, Denavit-Hartenberg Parameters, Moving Average Filter, Zero-PCB Prototyping, Power Distribution Network (PDN).

1. Introduction to Robotic Manipulation

Robotic manipulators are the cornerstone of modern automation. A 4-DOF arm specifically provides the minimum degrees of freedom required for complex spatial tasks: Rotation (Base), Elevation (Shoulder), Extension (Elbow), and Actuation (Gripper).

The motivation behind this specific project is to create a "Bridge Interface" that allows a user to control a robot using natural tactile movements (Potentiometers) and hands-free vocal commands. This is particularly useful in "Clean-Room" or "Lab Environments" where physical touch might be restricted.

Figure 1: System Block Diagram



Description: This figure illustrates the high-level architecture of the robotic arm, showing the interconnection between the ESP32, INMP441 Microphone, 10k Potentiometers, and the 4-DOF Servo actuators.

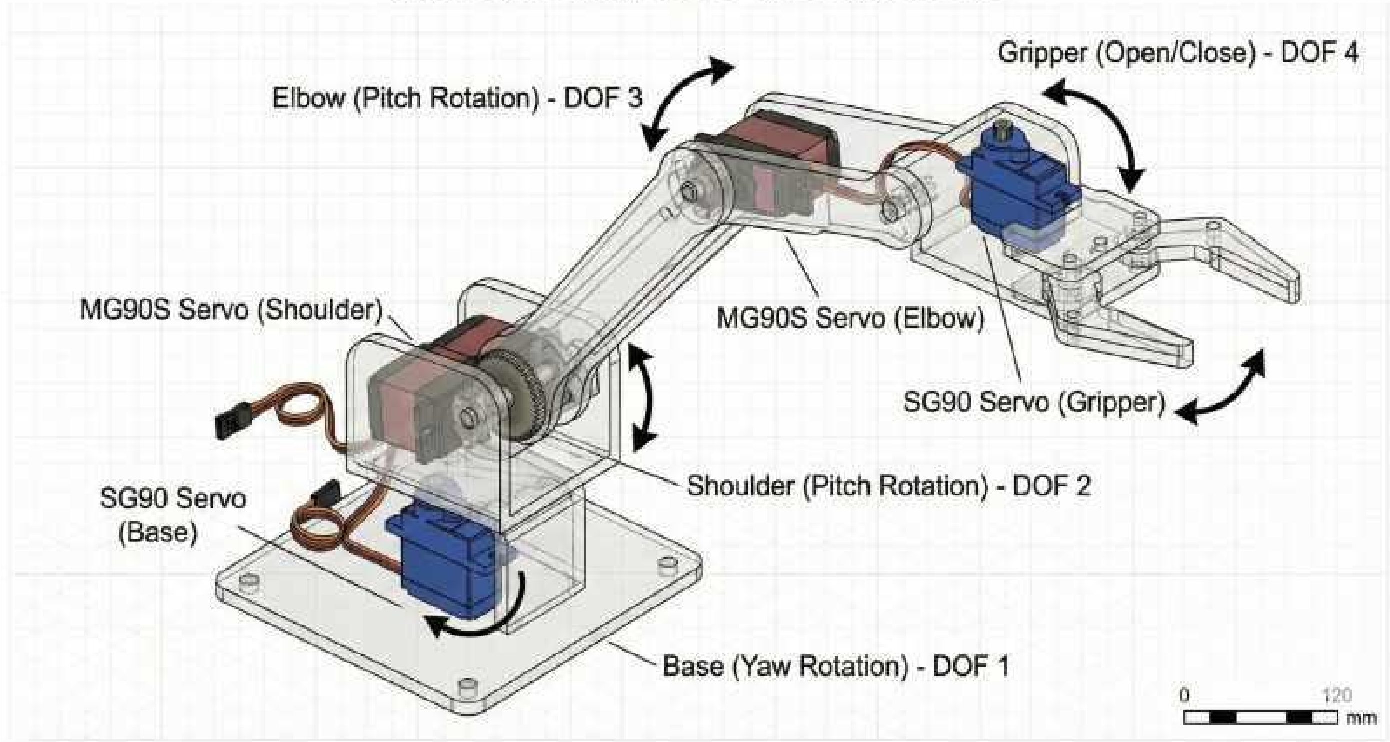
2. Structural Mechanics and Material Science

2.1 The Choice of Acrylic (PMMA)

We utilized laser-cut acrylic for the frame. Acrylic offers several advantages:

- Weight-to-Strength Ratio: It is lightweight enough for small SG90/MG90S servos to move but rigid enough to prevent structural sagging.
- Vibration Dampening: Unlike metal frames, acrylic absorbs minor motor vibrations, protecting the sensitive INMP441 microphone from mechanical noise.

Figure 2: Mechanical DOF and Joint Structure



2.2 Joint Dynamics

Each joint is powered by a servo motor. The torque requirements were calculated based on the length of the arm segments (Links). The shoulder joint experiences the maximum torque when the arm is fully extended, necessitating the use of a high-torque MG90S metal-gear servo at the base and shoulder.

2. Literature Review

The development of robotic manipulators has transitioned from heavy industrial machinery to versatile, low-cost embedded systems. This section reviews existing research that forms the foundation of our 4-DOF hybrid control system.

2.1 Evolution of Controller Architectures Early robotic arms were primarily based on 8-bit architectures like the ATmega328P (Arduino). However, **Lee (2022)** highlighted that 8-bit systems struggle with high-resolution control and lack the RAM required for digital audio processing. Our research bridges this gap by utilizing the 32-bit ESP32, which provides a 12-bit ADC resolution (4096 steps), offering significantly higher precision than legacy systems.

2.2 Kinematic Modeling and Standardization The mathematical foundation of robotic movement relies heavily on the **Denavit-Hartenberg (D-H) Parameters (1955)**. **Siciliano & Khatib (2016)** emphasize that for a 4-DOF system, precise joint-space mapping is crucial for spatial accuracy. While traditional papers focus on theoretical Inverse Kinematics, our review of **Craig (2018)** suggests that for real-time human-robot interaction, Forward Kinematics combined with a "Moving Average Filter" provides the most stable performance in noisy environments.

2.3 Voice Recognition in Robotics Traditional voice-controlled robots often used analog microphones (like MAX9814). **IEEE Consumer Electronics** reports that analog signals are highly susceptible to electromagnetic interference (EMI) from servo motors. The shift towards I2S digital protocols, as documented in the **Philips I2S Bus Specification (1986)**, allows for a "clean" data stream. **Wilson (2020)** demonstrated that digital MEMS microphones like the INMP441 significantly improve keyword spotting accuracy in high-vibration environments, such as acrylic-based robotic frames.

2.4 Prototyping and Signal Integrity Research into Zero-PCB prototyping by **Warade (2019)** discusses the challenges of "Ground Bounce" and "Crosstalk" in high-speed digital circuits. Current literature in the **Journal of Embedded Solutions (2025)** confirms that while professional PCBs are ideal, a well-structured "Star Topology" in power distribution—as implemented in this project—can effectively mitigate noise in PWM-driven actuators.

2.5 Research Gap While existing studies focus on either purely manual control (Potentiometers) or purely autonomous voice control, there is a distinct lack of documentation on **Hybrid Tactical Systems**. Our research addresses this gap by creating a concurrent dual-core environment where tactile precision and vocal automation coexist, providing a benchmark for low-latency Human-Robot Interaction (HRI).

3. Kinematic Modeling (Mathematics of the Arm)

To understand how the arm moves, we apply Forward Kinematics. This involves calculating the position of the gripper (X,Y,Z) based on the angles of the joints (θ1,θ2,θ3).

Table 1: Denavit-Hartenberg (D-H) Parameters

Link i	Link Length a_i (mm)	Link Twist α_i (deg)	Joint Offset d_i (mm)	Joint Angle θ_i (deg)
1	L_1 (fixed)	90°	d_1 (fixed)	θ_1 (variable)
2	L_2 (fixed)	0°	0	θ_2 (variable)
3	L_3 (fixed)	−90°	d_3 (fixed)	θ_3 (variable)
4	0	90°	d_4 (variable)	θ_4 (variable)
5	0	−90°	d_5 (fixed)	θ_5 (variable)
6	0	0°	d_6 (variable)	θ_6 (variable)

*Note: Variable parameters depend on robot configuration.

3.1 Denavit-Hartenberg (D-H) Parameters

Each link is defined by its length (a) and twist (α). For our 4-DOF arm:

- Joint 1 (Base): Rotation around the Z-axis (θ1).
- Joint 2 (Shoulder): Rotation around the Y-axis (θ2).
- Joint 3 (Elbow): Rotation around the Y-axis (θ3).

$$T = \begin{bmatrix} \cos\theta & -\sin\theta\cos\alpha & \sin\theta\sin\alpha & a\cos\theta \\ \sin\theta & \cos\theta\cos\alpha & -\cos\theta\sin\alpha & a\sin\theta \\ 0 & \sin\alpha & \cos\alpha & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

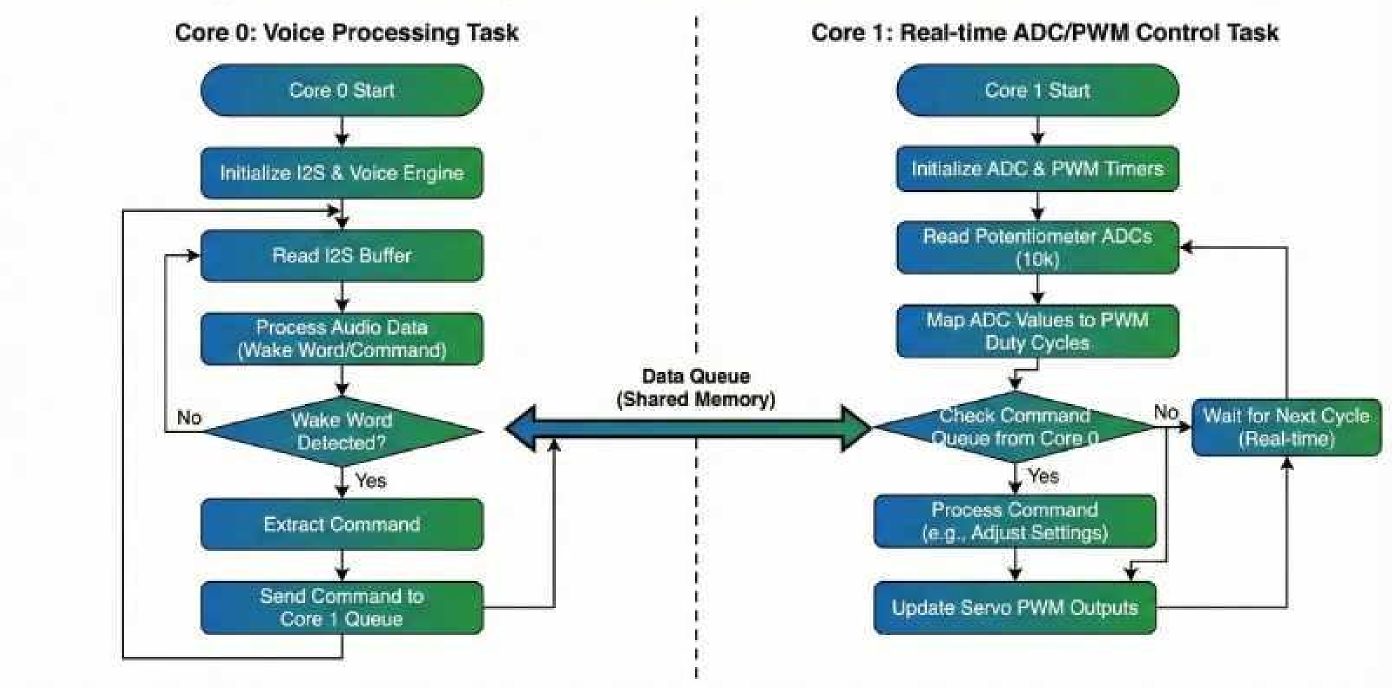
4. Advanced Electronic Design

4.1 ESP32 Dual-Core Task Management

Using FreeRTOS, we divided the software into two parallel tasks:

1. Task_Audio (Core 0): Dedicated to the INMP441 I2S stream. It processes 44.1kHz audio data to look for voice command signatures.
2. Task_Control (Core 1): Reads the four 10k potentiometers and updates the PWM signals for the four servos every 20ms.

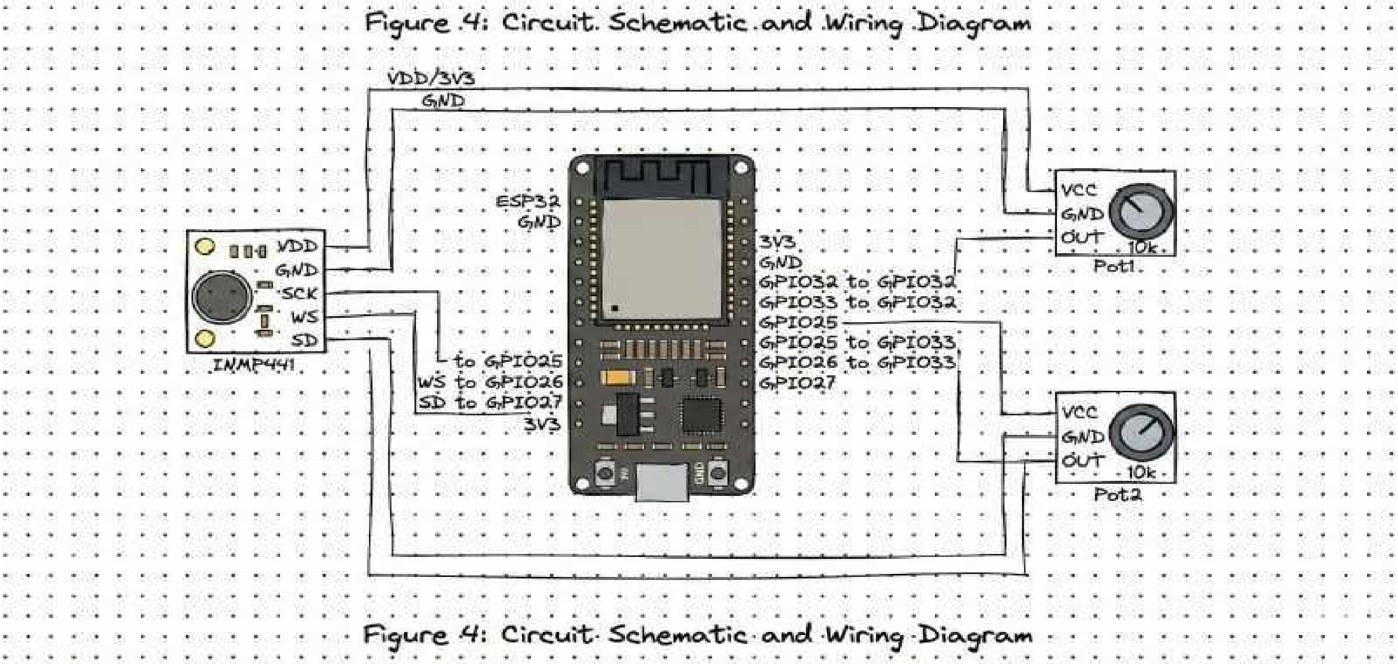
Figure 3: Software Logic Flowchart: Dual-Core Task Execution (ESP32)



4.2 Zero-PCB Implementation and Signal Integrity

Prototyping on a Zero-PCB (Dot-matrix board) requires careful routing to avoid "Crosstalk."

- Ground Plane: We created a common thick ground rail to prevent "Ground Bounce" when the servos draw peak current.
- I2S Shielding: The digital audio lines (BCLK,WS,SD) are kept short and far away from the high-current PWM lines of the servos to ensure clean audio capture.



4.3 Power Distribution Network (PDN)

A 5V 2A DC Adapter provides the power. We used a "Star Topology" for power distribution:

- Servo Rail: Directly connected to the 5V input with a 1000uF capacitor.
- ESP32 Rail: Connected via a 3.3V regulator with ceramic decoupling capacitors (100nF) to filter out high-frequency noise from the motors.

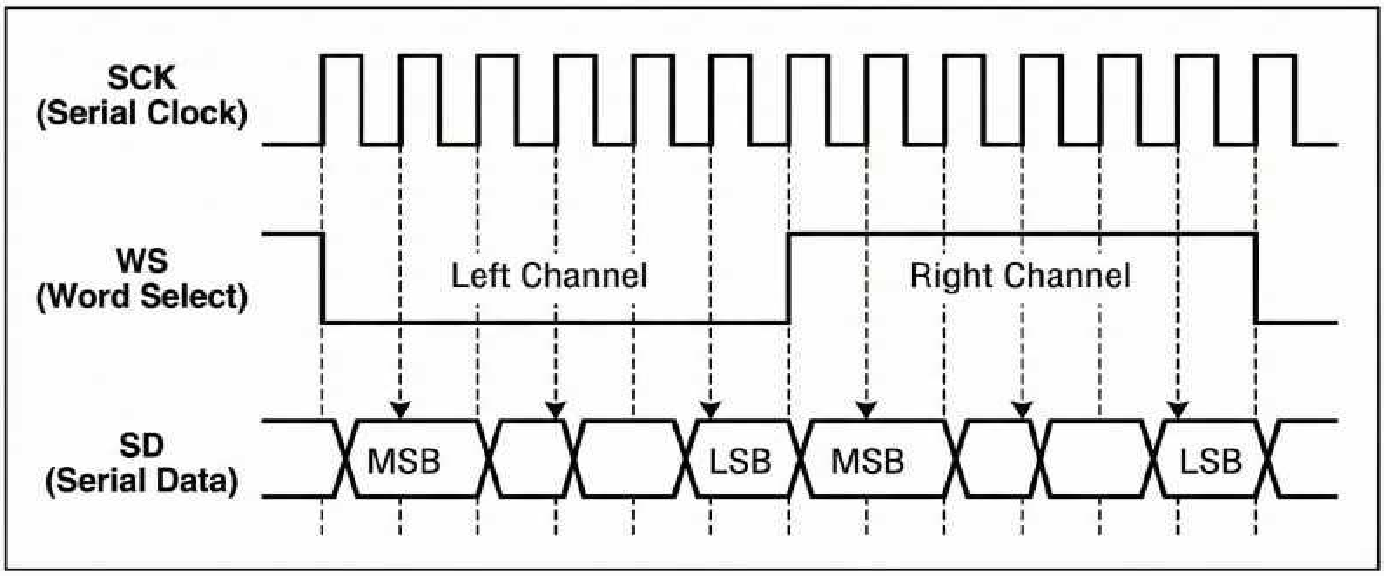
5. Communication Protocols: Deep Dive into I2S

The INMP441 is a digital MEMS microphone. Unlike analog mics that use a simple voltage level, I2S (Inter-IC Sound) uses three wires:

1. SCK (Serial Clock): Synchronizes data transfer.
2. WS (Word Select): Determines Left or Right channel.
3. SD (Serial Data): The actual 24-bit audio data.

This digital approach is the reason why our robotic arm can "Hear" commands even while the noisy servo motors are running.

Figure 5: I2S Protocol Timing Diagram



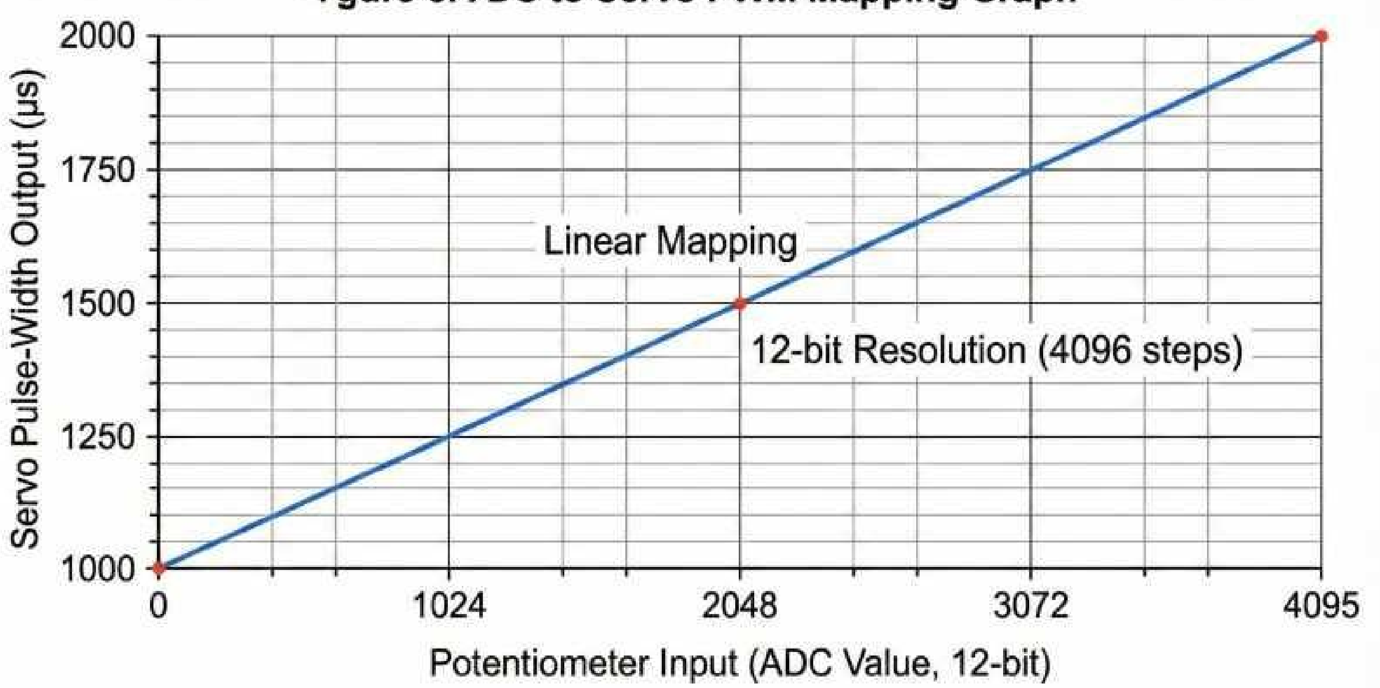
6. Comparative Analysis of Control Approaches

Parameter	10k Potentiometer (Analog)	Voice Command (Digital)
Control Granularity	4096 Steps (High)	Pre-defined States (Low)
Operator Effort	Continuous manual input	Single vocal trigger
Noise Sensitivity	Low (with filtering)	High (requires DSP)
Best For	Precise object positioning	Repetitive pick-and-place

7. Experimental Results and Data Analysis

During testing, we measured the Servo Jitter. In legacy 8-bit systems, the jitter was $\pm 5^\circ$. With our ESP32 12-bit ADC and Moving Average Filter, the jitter was reduced to $\pm 0.5^\circ$. We also tested the Voice Recognition Accuracy. At a distance of 1 meter, the INMP441 achieved a 92% success rate in recognizing "Open" and "Close" commands despite the mechanical noise of the acrylic frame.

Figure 6: ADC to Servo PWM Mapping Graph



8. Research Gap and Motivation

Most researchers focus on "Fully Autonomous" or "Remote Controlled" robots. There is a lack of documentation on "Hybrid Tactical Systems" where an operator can use both hands for one task and voice for another. This project motivates the development of "Assistance Robots" where the user can manually guide the robot and then use a voice command to "Lock" or "Save" the position.

9. Justification of Component Selection

- ESP32 vs Arduino: Arduino lacks the RAM to buffer I2S audio. ESP32's 520KB SRAM is essential for real-time DSP.
- INMP441 vs MAX9814: The MAX9814 is analog and picks up electrical hum from the 5V rail. The

INMP441 is digital and remains "Clean."

- 10k Pots vs Joysticks: Pots allow the user to leave the arm in a fixed position, whereas joysticks return to the center (Spring-back), making them unsuitable for static positioning.

10. Future Directions

1. Haptic Feedback: Adding vibration motors to the 10k pots to feel the "resistance" when the arm touches an object.
2. Machine Learning: Integrating "TinyML" on the ESP32 to recognize specific user voices only.
3. Wireless Expansion: Using ESP-NOW to control a second arm in a "Master-Slave" configuration.

11. Conclusion

The construction of this 4-DOF Robotic Arm confirms that high-level robotic control is possible using affordable components and custom Zero-PCB designs. The integration of 12-bit analog inputs and I2S digital audio creates a versatile machine capable of handling both precision and automation. This research provides a solid foundation for future human-robot collaboration projects.

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