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Design and implementation of a low-cost hybrid control architecture for a 4-DOF robotic arm

Nasiru Abdulsalam [1, *], Zaid Musa Imam [2], Jimoh Babatunde Olawale [3], Tikuochi Iheukwumere [4], Abdulfatah Munirudeen Olatunji [5], Guiryamadji Arnaud [6], Muhammad Aminu Ahmad [7] and Litima Nuhu [8]

[1] *Department of Electrical and Electronics Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, (ATBU), P.M.B. 0248, Bauchi, Nigeria.*
[2] *Department of Mechatronics and Systems Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, (ATBU), P.M.B. 0248, Bauchi, Nigeria.*
[3] *Department of Computer Engineering, Faculty of Engineering, Obafemi Awolowo University, (OAU), Osun State, Nigeria.*
[4] *Department of Mechatronics Engineering, Faculty of Engineering, University of Port Harcourt, Rivers State, Nigeria*
[5] *Department of Computer Science, Faculty of Computing, Abubakar Tafawa Balewa University, (ATBU), P.M.B. 0248, Bauchi, Nigeria.*
[6] *Department of Electrical and Electronics Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, (ATBU), P.M.B. 0248, Bauchi, Nigeria.*
[7] *Department of Electrical and Electronics Engineering, Faculty of Engineering and Engineering Technology, Federal Polytechnic Bauchi, Bauchi State, Nigeria.*
[8] *Department of Mechatronics and Systems Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, (ATBU), P.M.B. 0248, Bauchi, Nigeria.*

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Abstract

The increasing demand for affordable and intelligent robotic manipulators has driven research toward hybrid control architectures that combine precision, adaptability, and real-time feedback. This paper presents the design and implementation of a four-degree-of-freedom (4-DOF) robotic arm employing a low-cost ESP32 microcontroller as the central control unit. The system integrates a hybrid Human–Machine Interface (HMI) comprising both a physical joystick and an Android-based Bluetooth application, thereby enabling flexible user interaction and redundancy in control. To enhance safety and manipulation intelligence, a Force-Sensing Resistor (FSR) was incorporated into the gripper to provide real-time force feedback, allowing adaptive grip control and preventing object damage. The mechanical subsystem was actuated using three DC geared motors and a servo motor, driven through dual L298N motor drivers, while a TFT display provided real-time feedback on control mode and sensor data. Experimental validation demonstrated that the system achieved a latency of less than 20 ms for joystick control and approximately 100-150 ms for Bluetooth control, both within acceptable operational limits. The FSR feedback effectively detected applied forces up to 4.5 N, ensuring compliant grasping of fragile and rigid objects. The results confirmed that the proposed architecture achieved high functionality, responsiveness, and user adaptability, bridging the gap between simple open-loop systems and costly industrial manipulators. The developed prototype serves as a scalable and replicable model for educational, research, and low-cost automation applications.

Keywords: 4-DOF Robotic Arm; ESP32 Microcontroller; Hybrid Control System; Human–Machine Interface (HMI); Bluetooth Communication; Force-Sensing Resistor (FSR); Sensor Fusion; Low-Cost Robotics; Real-Time Control

* Corresponding author: Nasiru Abdulsalam.

1. Introduction

The evolution of robotics has been marked by an extraordinary transition from mechanically constrained devices to intelligent and interactive systems capable of complex decision-making and autonomous operation. At the core of this technological transformation lies the robotic manipulator, a mechanical system engineered to emulate the dexterity and motion of the human arm. These systems, broadly applied in industrial automation, healthcare, and research, have progressively advanced from simple preprogrammed actuators to highly responsive, sensor-driven platforms capable of human-machine collaboration. The measure of a manipulator's versatility and motion capability is often expressed in Degrees of Freedom (DOF) the number of independent joint movements that define its operational flexibility. Although higher DOF systems offer enhanced dexterity, they also introduce substantial challenges in modeling, control, and computation collectively known as the Degrees of Freedom problem [1].

Within this context, four-degree-of-freedom (4-DOF) manipulators have emerged as a pragmatic compromise between mechanical complexity and functional capability. They are particularly attractive for low-cost, educational, and research-oriented applications, providing sufficient dexterity for essential pick-and-place operations without the intricacies associated with 6-DOF industrial manipulators [2], [3]. The balance between simplicity, affordability, and operational flexibility makes 4-DOF robotic arms ideal for demonstrating fundamental principles of kinematics, control theory, and sensor integration in academic environments.

Central to the functionality of any robotic manipulator is its control architecture, which serves as the computational bridge between human intent and mechanical execution. Historically, robotic arms relied on centralized wired control systems, often characterized by high performance but significant expense, limited scalability, and cumbersome wiring [1]. The introduction of embedded microcontrollers revolutionized this paradigm, enabling smaller, modular, and more affordable control solutions that democratized robotic experimentation [2]. In recent years, microcontrollers such as the ESP32 have gained prominence due to their dual-core processing capability, built-in Wi-Fi and Bluetooth communication, and low power consumption, making them ideal for real-time robotic applications and Internet of Things (IoT) integration [4], [5]. This evolution in embedded processing has reduced the barrier to entry for intelligent robotic design, allowing researchers and educators to develop high-performance systems at minimal cost.

Another crucial dimension of modern robotic design is Human-Machine Interaction (HMI). The interface through which a human operator communicates with a robot fundamentally determines usability, intuitiveness, and control accuracy [6]. Conventional joystick-based interfaces remain widely adopted for their tactile feedback and real-time responsiveness [7]. However, the widespread proliferation of smartphones has introduced new possibilities for wireless control, featuring graphical interfaces and customizable layouts that simplify configuration and extend functionality [8]. Each modality joystick and smartphone present distinct advantages and trade-offs. While joysticks offer superior precision and instantaneous feedback, smartphones provide flexibility, portability, and user interface adaptability [9]. Recent studies have emphasized the value of hybrid HMI systems, which integrate both modalities to enhance robustness and user experience [10]. Such hybrid approaches improve resilience against input failure, enable context-dependent control, and cater to a wider range of user preferences and operational environments.

Beyond motion control, force feedback is increasingly recognized as essential for safe and intelligent robotic operation. Force sensing enables manipulators to detect and respond to contact forces, thereby preventing damage to fragile objects, ensuring stable grasping, and allowing safe physical interaction with humans [11]. While advanced force and torque sensors such as strain gauges and capacitive transducers offer high precision, they are often expensive and unsuitable for low-cost educational platforms. Force-Sensing Resistors (FSRs) provide a cost-effective alternative, offering adequate sensitivity and compactness for implementing basic force feedback loops in robotic grippers [12]. The inclusion of FSRs allows a robotic system to "sense" grip force and react accordingly, a fundamental step toward more adaptive and intelligent manipulation behavior.

The synergy between low-cost microcontrollers, hybrid control modalities, and affordable sensing technologies forms the cornerstone of this study. Although numerous works have explored joystick-controlled systems [4], Bluetooth-based smartphone interfaces [5], or force feedback mechanisms individually [12], existing research rarely combines these elements into a unified, scalable, and low-cost control architecture. This lack of integration represents a significant research gap, particularly for applications requiring both operational flexibility and sensory adaptability under resource constraints. Furthermore, the absence of force feedback in most low-cost robotic arms limits their usability for delicate or interactive tasks, while reliance on a single control mode reduces system redundancy and user versatility.

To address these limitations, this paper presents the design and implementation of a hybrid-controlled 4-DOF robotic arm based on the ESP32 microcontroller, integrating joystick and Android-Bluetooth interfaces with FSR-based force feedback. The ESP32's dual-core architecture allows concurrent execution of communication and control tasks, ensuring real-time performance even with multi-modal input streams. The robotic arm, actuated by DC geared motors and a servo gripper, incorporates an FSR sensor in the gripper to monitor applied pressure and prevent object deformation. The dual-control HMI enables users to seamlessly switch between tactile joystick control and smartphone-based wireless operation, thus enhancing usability and system adaptability.

The objectives of this study are threefold: (1) to develop a 4-DOF robotic arm prototype using a hybrid joystick and Bluetooth control scheme; (2) to integrate FSR-based force feedback for adaptive gripping and safe object handling; and (3) to evaluate system performance in terms of responsiveness, accuracy, and user experience. The results of the experimental evaluation demonstrate that the proposed architecture achieves low-latency control, effective force adaptation, and high operational flexibility, positioning it as a valuable contribution to low-cost robotics, automation education, and human–robot interaction research.

2. Literature review

Research in robotic manipulators and hybrid control systems has evolved through successive stages of mechanical design, embedded control, and sensor-based intelligence. The following review synthesizes prior contributions across these domains, emphasizing how the present work extends existing knowledge on low-cost hybrid control architectures and force-feedback-enabled manipulators.

2.1. Robotic Arm Design and Control Architectures

Early studies focused on the mechanical design and actuation of low-degree-of-freedom robotic arms. Mustaffa et al. [17] developed a 4-DOF prototype employing DC geared motors and ABS-fabricated links, confirming basic motion feasibility but encountering joint misalignments due to heavy metal gearing. Similarly, Yunusa et al. [25] implemented a 4-DOF robotic arm using an Arduino Uno controller and servo actuation. While their prototype achieved a payload of 0.058 kg and accurate motion at 180° base rotation, it lacked integrated sensing or wireless control capability. These limitations underscored the need for higher-performance embedded platforms.

Recent investigations transitioned toward ESP32-based architectures, exploiting its dual-core processing and wireless connectivity. Labade et al. [11] designed a robotic arm vehicle controlled via a PlayStation 3 controller over Bluetooth, demonstrating seamless operation but constrained by a single control mode. Kiranmayi et al. [9] proposed a Bluetooth-based mobile robot driven through an Android application, validating real-time low-latency communication but offering no tactile control option. Kuppuswamy et al. [10] achieved wireless joystick operation using the ESP32, enhancing manual precision yet omitting smartphone integration. Collectively, these works highlight the feasibility of ESP32-based robotic systems but reveal a clear absence of multimodal HMI designs.

2.2. Hybrid Control and Human-Machine Interaction

Human-Machine Interaction (HMI) theory emphasizes the role of intuitive, ergonomic, and multimodal control interfaces [5]. Joysticks remain prominent for their direct analog feedback and real-time responsiveness [14], whereas touchscreen and smartphone interfaces have gained popularity for their accessibility and configuration flexibility [22]. However, as Wu and Liu [22] demonstrated, touchscreen control while convenient often introduces perceptible latency and reduced tactile feedback compared to physical joysticks.

Dritsas et al. [5] concluded that multimodal or hybrid interaction architectures enhance usability and system robustness by allowing complementary modes of operation. Despite these insights, most robotic arm designs in literature rely on a single interface, either joystick [10] or smartphone [6], without enabling dual-mode interaction. The lack of hybrid HMI integration represents a persistent limitation that this study directly addresses by fusing joystick precision with Bluetooth-based mobile flexibility within one unified control framework.

2.3. Force Feedback and Sensor Integration

Accurate force perception is vital for safe manipulation and adaptive control. Li and Xu [12] reviewed multi-axis force/torque sensors and emphasized their importance in achieving compliant interaction but noted cost barriers to adoption in low-budget systems. Yang et al. [24] demonstrated the effectiveness of sensor fusion using vision, gesture, and force feedback sensors in anthropomorphic teleoperation, achieving improved accuracy but suffering from communication delay issues. Mahfouz et al. [15] analyzed end-effector control strategies for rehabilitation robots and highlighted that adaptive impedance and sliding-mode controllers outperform conventional PID in managing interaction forces though at higher computational cost.

In contrast, low-cost robotic designs such as those by Daga et al. [3] and Yunusa et al. [25] omit any form of tactile sensing. The present study advances the field by integrating Force-Sensing Resistors (FSRs) to deliver proportional feedback at minimal expense, bridging the gap between cost-efficiency and sensory capability.

2.4. Control Methodologies and Embedded Platforms

Tinoco et al. [21] provided a comprehensive review of modern control paradigms adaptive, robust, fuzzy, and neural approaches highlighting their superior performance but high implementation complexity on limited microcontrollers. De Luca et al. [4] earlier demonstrated the robustness of hybrid dynamic control, whereas Spong [19] contextualized the historical progression of manipulator control, noting the transition from open-loop to feedback-dominated architectures. These foundational studies establish the theoretical underpinning of feedback integration exploited in the proposed design.

The ESP32 platform merges real-time processing with wireless connectivity, allowing distributed control and sensor fusion within constrained budgets [11]. Licardo et al. [13] and Avesahemad et al. [1] further documented the broader trend toward intelligent, sensor-aware, and collaborative robotics, reinforcing the relevance of affordable yet capable embedded systems.

2.5. Identified Knowledge Gap

Synthesizing the reviewed literature reveals a consistent gap: while numerous low-cost robotic arms exist, they typically employ single-mode HMIs and lack integrated force feedback. Advanced force-controlled manipulators, conversely, depend on costly sensors and complex algorithms unsuitable for budget-constrained educational use. Consequently, no unified design currently demonstrates a hybrid joystick–Bluetooth control architecture with FSR-based tactile sensing on a single ESP32 platform.

This study addresses that gap by presenting a 4-DOF robotic arm that fuses these elements into a cohesive, low-cost, and scalable system thereby contributing a novel architecture for adaptive, human-centric robotic manipulation.

3. Methodology

3.1. Overview of System Architecture

The proposed 4-degree-of-freedom (4-DOF) robotic arm was designed as an intelligent, low-cost manipulator centered around the ESP32 microcontroller, integrating dual control interfaces and real-time force feedback. The overall system architecture consists of five primary subsystems: control unit, power supply unit, human-machine interface (HMI) unit, sensing unit, and actuation unit, as shown in Fig. 1.

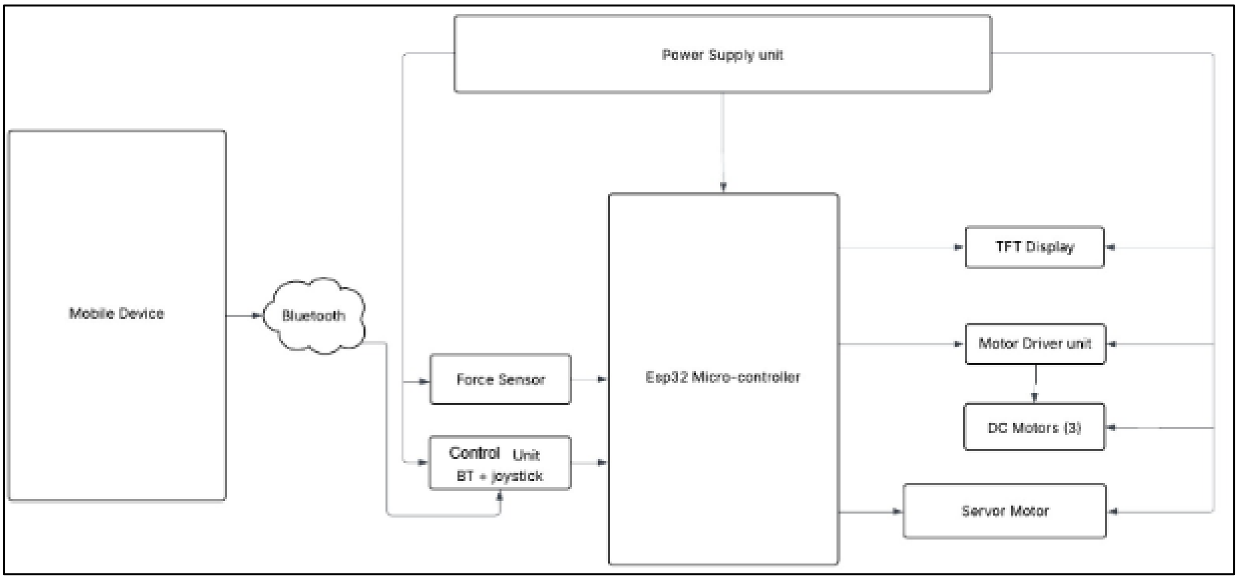

Figure 1 System Block Diagram

The ESP32 microcontroller serves as the system's central processing hub, responsible for receiving user inputs, interpreting control commands, executing feedback algorithms, and generating motor control signals. Its dual-core processor enables concurrent execution of wireless communication tasks and real-time actuation loops without performance degradation.

The power supply unit comprises a 3S (11.1 V) lithium-ion battery pack, protected by a battery management system (BMS), and a buck converter (LM2596) that steps down the voltage to 5 V for the logic-level components. This configuration ensures efficient energy utilization and prevents voltage fluctuations during peak current draw from motors.

The HMI unit integrates two complementary control modalities

- Joystick Mode: Two analog joysticks provide direct tactile control for high-precision, real-time motion of the robotic joints.
- Bluetooth Mode: A custom Android application transmits digital commands via the ESP32's built-in Bluetooth serial interface, enabling remote operation and enhanced user flexibility.

The sensing unit consists of a Force-Sensing Resistor (FSR) embedded in the gripper, which provides proportional feedback corresponding to the contact pressure during object manipulation. The actuation unit translates these control signals into physical motion using three 12 V DC geared motors for the base, shoulder, and elbow joints, and one SG90 micro servo for the gripper. Two L298N motor driver modules manage speed and direction control through pulse-width modulation (PWM).

A 2.8-inch ILI9341 TFT display provides visual feedback of system status, control mode, and sensor readings in real time, ensuring user transparency and interaction awareness.

3.2. Justification of the 4-DOF Configuration

The design adopts a 4-DOF configuration comprising base rotation, shoulder pitch, elbow pitch, and gripper motion as an optimal balance between functionality and simplicity. Systems with six or more degrees of freedom offer greater dexterity but also introduce computational and kinematic complexity, known as the Degrees of Freedom Problem [16].

A 4-DOF manipulator maintains sufficient versatility for essential planar pick-and-place operations while minimizing control burden, power demand, and cost. This configuration is especially suitable for educational and experimental applications, where modularity and affordability are prioritized over industrial-scale precision.

3.3. Hardware Implementation

The hardware design integrates readily available, cost-effective components to maximize performance per unit cost. Table I summarizes the major components and their technical specifications.

Table 1 Major Components of the System

Component	**Model**	**Function**	**Key Features**
Microcontroller	ESP32 Devkit	Central control unit	Dual-core, Wi-Fi/Bluetooth, 12-bit ADC
Motor Driver	L298N	DC motor driver	Dual H-bridge, 2 A/channel
Actuators	12 V DC geared motors & SG90 Servo	Arm and gripper actuation	High torque, low speed, lightweight
Force Sensor	FSR 402	Pressure feedback	Resistive sensing, low-cost, durable
Display	ILI9341 TFT (2.8")	User interface	SPI communication, 320×240 pixels
Power Supply	3S Li-ion Battery (11.1 V)	Power source	Rechargeable, BMS protection

The DC geared motors drive the main joints, providing adequate torque for lifting lightweight payloads (up to 120 g) while maintaining positional stability. The servo motor offers precise angular control for gripper motion. The FSR sensor, connected through a voltage divider circuit, allows the ESP32's ADC to monitor grip force dynamically.

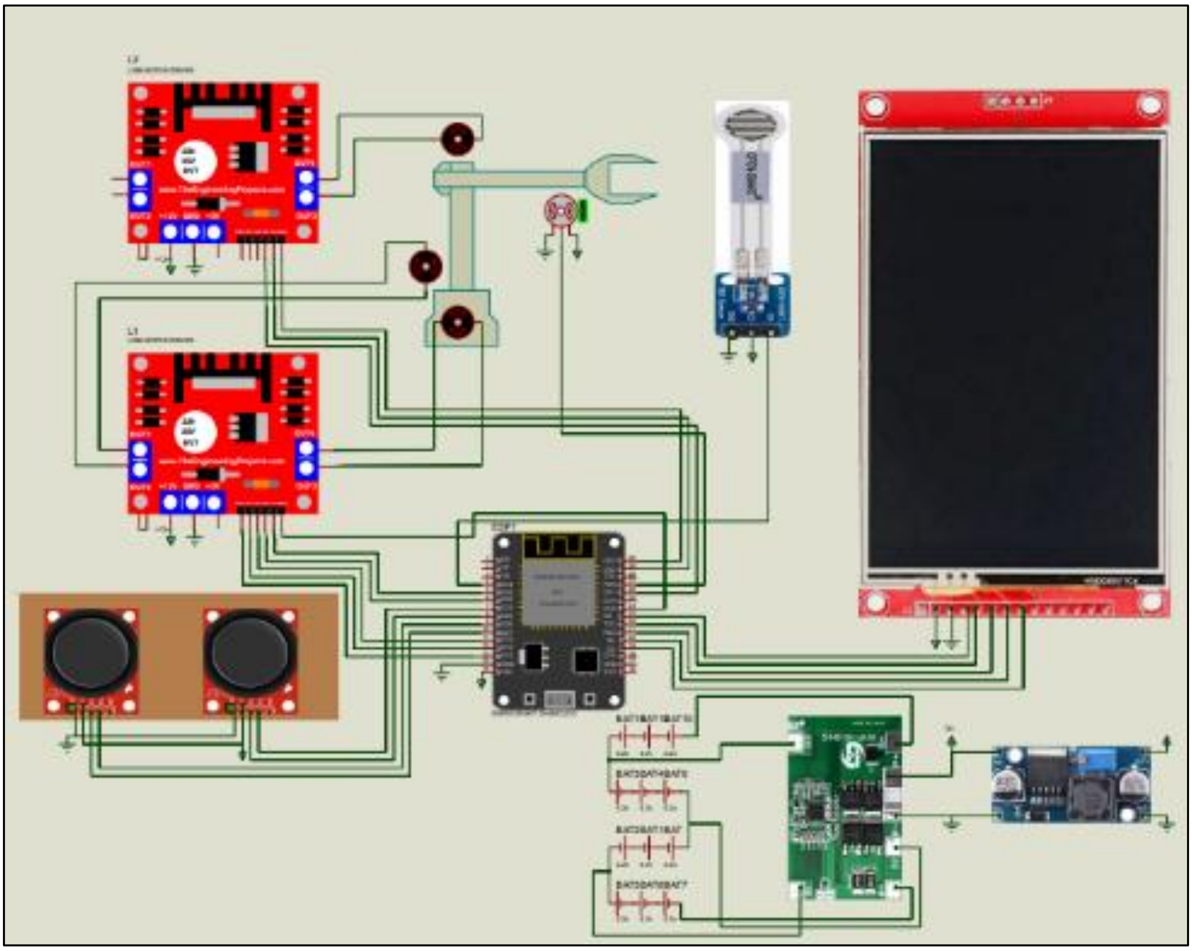

Figure 2 System Circuit Diagram

3.4. Software Design and Task Distribution

The control software was developed in C++ using the Arduino IDE, leveraging the ESP32's FreeRTOS kernel to allocate distinct tasks to its two cores, ensuring smooth multitasking and real-time performance.

- Core 0 (Communication & Display): Handles Bluetooth data reception, Wi-Fi/Bluetooth stack management, and periodic TFT display updates.
- Core 1 (Real-Time Control): Executes joystick input acquisition, PWM signal generation for motors, and force feedback processing from the FSR sensor.

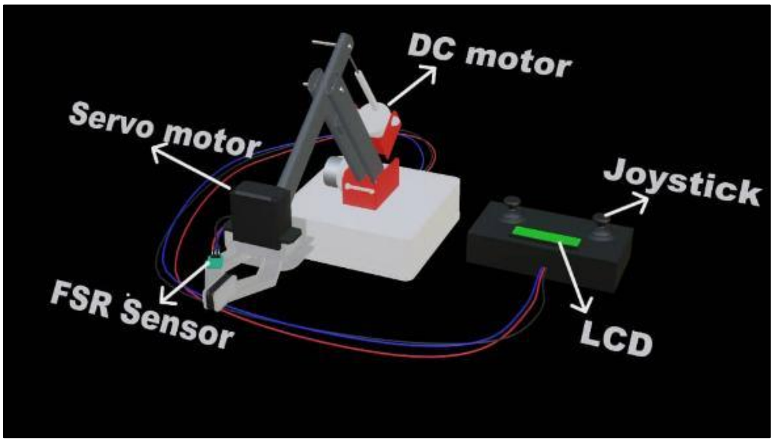

Figure 3 3D Model of the Robotic Arm

The main program is structured into modular functions for initialization, input reading, data processing, and actuation. The system flow logic is summarized as follows

3.4.1. Initialization

- Set up GPIO pins, initialize serial ports, configure display and Bluetooth modules.
- Display control options (Joystick or Bluetooth mode) on the TFT interface.

3.4.2. Mode Selection

- The user selects the desired control mode via touchscreen or pushes button.
- System enters corresponding loop for either joystick or Bluetooth control.

3.4.3. Real-Time Control Loop

- Joystick Mode: Analog inputs from joysticks are mapped to PWM duty cycles, controlling direction and speed of DC motors.
- Bluetooth Mode: Commands received as ASCII characters (e.g., “F” for forward, “G” for grip) are parsed and executed.

3.4.4. Force Feedback Control

- The gripper servo actuates until FSR readings exceed the defined threshold (≈ 2800 ADC counts ≈ 4.5 N).
- Upon threshold detection, servo motion halts automatically to prevent excessive gripping force.

3.4.5. Display Update

- The TFT display continuously shows real-time control mode, force readings, and system status.
- This architecture ensures low-latency analog response for manual control while maintaining wireless flexibility through Bluetooth communication.

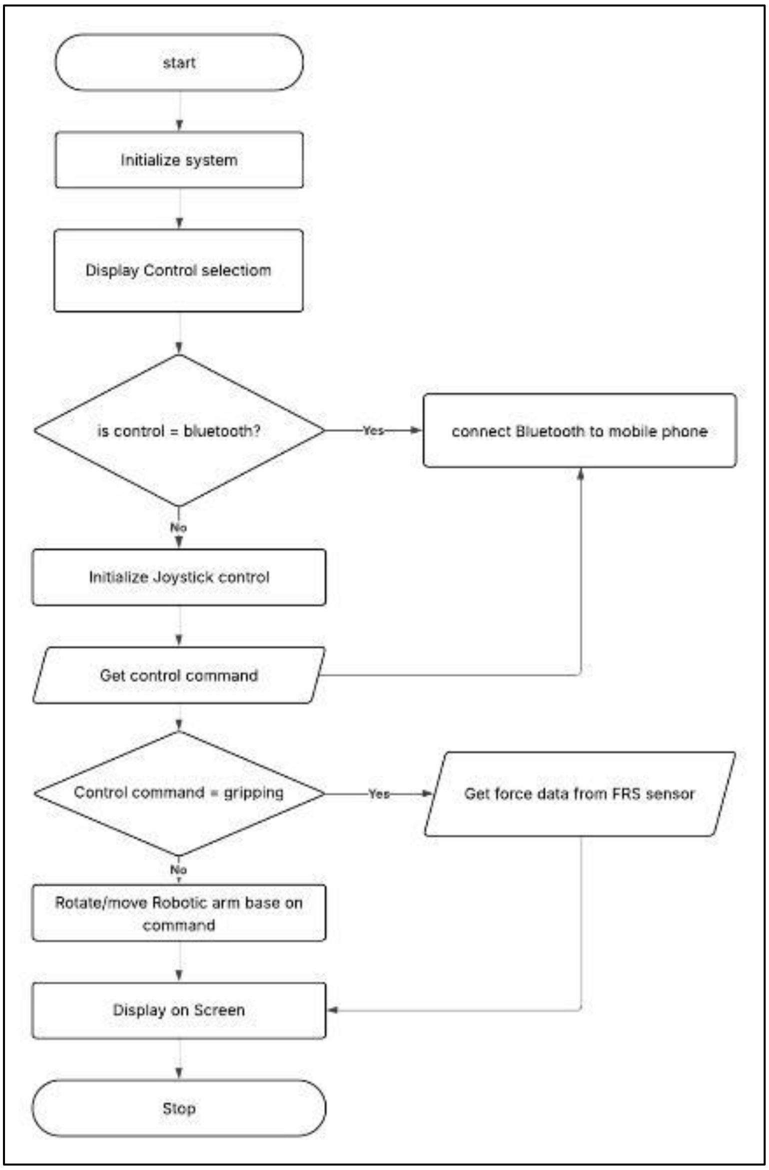

Figure 4 System Operation Flowchart

3.5. Theoretical Framework and Governing Equations

The system's mechanical and electrical behavior follows fundamental engineering principles that determine torque, power, and sensor response.

3.5.1. Mechanical Torque Analysis

For static equilibrium under gravitational loading, the required torque at any joint is given by

$$\tau = rF\sin\theta$$

where τ is torque (Nm), or is the distance from the pivot to the applied force (m), F = mg is the force due to mass (N), and θ is the angle between F and r.

3.5.2. For the elbow joint

$$\tau_{elbow} = \left(m_{forearm}g\frac{L_{forearm}}{2}\right) + \left(m_{gripper} + m_{payload}\right)gL_{forearm}$$

Similarly, the torque at the shoulder is:

$$\tau_{shoulder} = \left(m_{upper\_arm} g \frac{L_{upper\_arm}}{2}\right) + \left(m_{forearm} + m_{gripper} + m_{payload}\right) g \left(L_{upper\_arm} + L_{forearm}\right)$$

These relations guide actuator selection and verify that the motors provide sufficient torque for stable operation.

3.5.3. Electrical and Power Equations

The basic relationships governing voltage, current, and resistance are expressed by Ohm's and power laws:

$$V = IR$$

$$P = VI$$

Battery lifetime (T) for a given average current draw (Iavg) is estimated as:

$$T = \frac{C}{I_{avg}}$$

where C represents battery capacity in ampere-hours (Ah).

3.5.4. Sensor and Control Signal Conversion

The FSR sensor operates within a voltage divider, where output voltage (Vout) is determined by:

$$V_{out} = V_{supply} \frac{R_{fixed}}{R_{FSR} + R_{fixed}}$$

The analog-to-digital conversion of Vout into a digital value (DADC) on the ESP32 is given by:

$$D_{ADC} = \frac{V_{out}}{V_{ref}} (2^N - 1)$$

where Vref = 3.3V and N = 12 bits for the ESP32 ADC.

Motor speed control is achieved through Pulse Width Modulation (PWM), defined as:

$$V_{avg} = V_{supply} \times D$$

where D = $\frac{t_{on}}{T}$ represents the duty cycle ratio between high pulse duration (ton) and total period (T).

3.5.5. Android Application Development

A custom Android application, developed using MIT App Inventor, provides an intuitive graphical interface for remote control. The interface includes directional buttons (Base Left/Right, Shoulder Up/Down, Elbow Up/Down, Gripper Open/Close) and a Bluetooth connection manager. The app transmits predefined character commands via Bluetooth serial to the ESP32, which parses and executes them immediately. This approach provides cross-platform compatibility and allows easy modification of interface layouts for different user requirements, ensuring adaptability in both educational and assistive environments.

3.5.6. Experimental Methodology

System validation employed a two-stage testing protocol

- **Unit Testing:** Each subsystem (power, actuation, sensing, and interface) was independently tested to verify voltage stability, signal integrity, and actuator responsiveness.
- **System Integration Testing:** The fully assembled system was evaluated for real-time responsiveness, hybrid mode switching, and force feedback performance.

Latency was measured using an oscilloscope to capture the time difference between user input (analog joystick or Bluetooth command) and PWM output response. Each control mode was tested 30 times to compute average latency. Force feedback calibration established that 2800 ADC counts corresponded to approximately 4.5 N, ensuring delicate handling of lightweight objects.

4. Results

4.1. Experimental Setup and Validation Protocol

Comprehensive validation of the developed 4-DOF robotic arm was conducted through two principal stages: unit testing and system integration testing. Each subsystem power, actuation, sensing, and control interface was evaluated in isolation prior to full system integration. Testing focused on responsiveness, force feedback accuracy, and user interaction efficiency across both control modes (joystick and Bluetooth).

To quantify control latency, a digital oscilloscope was employed to measure the time difference between command input and actuator response. For the joystick mode, the oscilloscope simultaneously captured the analog output from the joystick and the PWM signal entering the motor driver. For Bluetooth mode, a GPIO pin was toggled high upon command reception to record transmission delay before the motor response. Each latency measurement represented the average of 30 repeated trials for statistical reliability.

4.2. Power System and Electrical Stability

Table II summarizes voltage stability measurements for both the logic and motor rails. The system exhibited excellent voltage regulation, remaining within ±1.5% of nominal values under both idle and loaded conditions.

Table 2 Power Distribution Stability Results

Measurement Point	Nominal Voltage (V)	Idle (V)	Under Load (V)
Motor Rail (L298N Input)	12.0	12.4	11.8
Logic Rail (Buck Output)	5.0	5.05	4.98

The battery management system (BMS) maintained overcurrent protection and thermal safety throughout extended operations. These results confirm the reliability of the designed power subsystem, ensuring stable logic operation and consistent motor torque without microcontroller resets.

4.3. Sensor Characterization and Force Feedback Calibration

The Force-Sensing Resistor (FSR) displayed a consistent response across the applied pressure range. At rest, the analog-to-digital converter (ADC) output averaged 45 counts, increasing linearly up to 3800 counts under firm pressure. A calibration process established that an ADC value of 2800 corresponds to approximately 4.5 N, equivalent to 0.46 kg.

This value was adopted as the safe gripping threshold, allowing the gripper to halt closure when contact pressure exceeds this limit. The FSR-based feedback loop effectively prevented damage to fragile objects (such as a paper cup requiring <3 N to deform) while maintaining secure grip on rigid materials. This demonstrates that even a low-cost FSR can enable adaptive manipulation comparable to more expensive capacitive or strain-gauge sensors [12], [15].

4.4. Hybrid Control Responsiveness and Latency

Performance comparison between control modes revealed significant differences in transmission characteristics, as summarized in Table III.

Table 3 Control Interface Performance Evaluation

Control Interface	Transmission Medium	Average Latency (MS)	User Feedback
Joystick Control	Direct Analog Signal	< 20	Instantaneous, highly responsive
Bluetooth Control	Serial via ESP32 Bluetooth	100-150	Slight delay, acceptable for general use

The analog joystick provided sub-20 MS latency, effectively imperceptible to the user, enabling precise, real-time joint manipulation. Conversely, the Bluetooth mode introduced a predictable delay of 100-150ms, primarily due to serial packet transmission and decoding overhead within the Bluetooth stack. Despite this, the delay remained within acceptable thresholds for non-critical or remote operations, corroborating similar latency trends reported in wireless control studies [9], [11].

The ability to seamlessly switch between joystick and Bluetooth modes from the TFT display validated the hybrid control architecture, improving system redundancy and flexibility an advancement over existing single-interface systems [6], [10].

4.5. Actuator Performance and Payload Capacity

During full-system testing, all joints responded smoothly and without perceptible jitter, indicating that the PWM control loop maintained stable duty cycles even under variable load conditions. The robotic arm achieved a maximum static payload capacity of 120 g at full horizontal extension, consistent with calculated torque limits derived from Eq. (2) and Eq. (3).

The positional repeatability of the end-effector was measured using visual markers and digital image analysis, yielding an average positional deviation of ±5 mm in Cartesian space at maximum reach. While this accuracy suffices for educational and light automation applications, it is limited compared to stepper- or encoder-based arms used in precision tasks [21]. The deviation is attributed to mechanical backlash inherent in low-cost DC geared motors a trade-off for affordability.

4.6. Functional Testing of Force-Feedback Gripper

The integrated gripper successfully demonstrated adaptive grasping across two test scenarios

- Fragile Object Test: When grasping a paper cup (<3 N compressive limit), the system halted servo motion immediately upon reaching the calibrated 2800 ADC threshold, preventing deformation.
- Rigid Object Test: When gripping a wooden block, the servo stopped automatically once full grip was achieved, avoiding motor stall and unnecessary energy consumption.
- These results verify the reliability of the FSR feedback loop in differentiating object stiffness and autonomously adapting grip strength. Compared to conventional open-loop grippers, the proposed system introduces a level of tactile awareness typically associated with higher-end manipulators [12], [24].

4.7. Comparative Discussion with Existing Studies

When benchmarked against prior low-cost robotic arms, the proposed system demonstrates distinct advantages in multimodal control and force feedback integration.

- Versus Arduino-based Designs: Yunusa et al. [25] achieved functional 4-DOF control but lacked wireless connectivity and feedback sensing. The ESP32-based system presented here surpasses such designs in processing speed and control versatility.
- Versus Single-Interface ESP32 Systems: Labade et al. [11] and Kiranmayi et al. [9] implemented either joystick or Bluetooth control independently. The hybrid control strategy developed in this study eliminates single-mode dependency, improving user adaptability and operational reliability.
- Versus Advanced Research Systems: While studies like Yang et al. [24] and Mahfouz et al. [15] integrated high-cost force sensors or adaptive impedance control for sophisticated robotics, their complexity and cost make them unsuitable for educational or hobbyist deployment. The present system achieves similar conceptual functionality adaptive gripping at a fraction of the cost.

This comparative analysis confirms that the developed 4-DOF arm fills a unique niche between affordable educational prototypes and advanced industrial manipulators, embodying the principles of scalability, low power consumption, and multimodal control.

5. Discussion on Limitations

Despite its success, several limitations were identified. The use of DC geared motors without encoder feedback introduces open-loop positional errors and limits precision for repetitive tasks. Additionally, Bluetooth latency, though acceptable, may hinder time-sensitive operations in multi-robot networks. The FSR sensor, while adequate for force threshold detection, exhibits nonlinearity and hysteresis at high pressures, reducing suitability for proportional force control applications. Future enhancements should therefore focus on incorporating closed-loop feedback, stepper or encoder-based actuators, and PID-based adaptive force regulation.

5.1. Overall Evaluation

The experimental outcomes demonstrate that the proposed ESP32-based hybrid control system successfully fulfills its design objectives

- Hybrid Operation: Seamless transition between joystick and Bluetooth control confirms dual-mode reliability.
- Responsive Performance: Achieved <20 MS latency for analog control and ≤150 MS for wireless operation.
- Adaptive Force Feedback: The FSR mechanism effectively prevents damage to fragile objects, validating tactile sensing capability.
- Operational Robustness: Stable power regulation and efficient multitasking affirm the ESP32's suitability for embedded robotics.

6. Conclusion

This study successfully designed, implemented, and evaluated a 4-degree-of-freedom (4-DOF) robotic arm employing a hybrid control architecture powered by the ESP32 microcontroller. The system integrates dual control modalities a physical joystick and a Bluetooth-enabled Android interface alongside force feedback sensing through a Force-Sensing Resistor (FSR). The convergence of these technologies established a flexible, responsive, and cost-efficient robotic manipulator capable of performing real-time object handling with adaptive grip control.

Experimental validation demonstrated that the system achieved latency values below 20 ms in joystick mode and 100-150 ms in Bluetooth mode, well within acceptable limits for low-cost robotic platforms. The FSR-based feedback enabled the gripper to detect and respond to forces up to 4.5 N, ensuring compliant interaction with both fragile and rigid objects. These results confirm that intelligent tactile feedback and multimodal human–machine interfaces can be realized on affordable hardware without compromising functionality or stability.

Compared with existing designs [6], [9], [10], [11], [25], the proposed system delivers superior adaptability by integrating dual operational modes within a single embedded framework, while the inclusion of FSR feedback introduces basic sensory intelligence absent in conventional low-cost manipulators. The modular design allows straightforward reconfiguration and scalability, enabling its application across educational robotics, assistive technology, and light-duty automation.

The findings contribute substantively to the growing domain of low-cost intelligent robotics, bridging the divide between open-loop academic prototypes and expensive industrial manipulators. Furthermore, the integration of real-time force feedback with hybrid human–machine interaction (HMI) represents a significant step toward democratizing robotics education and research accessibility in resource-constrained environments.

Recommendations for Future Work

- Although the proposed 4-DOF robotic arm achieved its performance objectives, several avenues exist for enhancement and further research
- Incorporating rotary encoders or Hall-effect sensors will enable position and velocity feedback, reducing positional drift and improving motion repeatability for precision applications.
- The current FSR implementation, though effective for threshold detection, could be upgraded to a multi-axis force/torque sensor [12] to capture detailed contact dynamics, enabling proportional grip control and object classification through tactile sensing.
- The deployment of PID, adaptive, or fuzzy logic controllers [21] could further stabilize joint motion, reduce overshoot, and enhance response under varying load conditions. Implementation using the ESP32's real-time capabilities remain feasible with efficient task scheduling.
- The addition of a camera module and image-processing unit could allow visual servoing, object recognition, and autonomous pick-and-place tasks, advancing the system from user-guided control to semi-autonomous manipulation.
- Leveraging the ESP32's Wi-Fi interface, future iterations may adopt IoT-based remote monitoring and cloud-based data logging for real-time performance visualization and teleoperation across distributed environments.

- The structural frame, currently built with lightweight materials, can be reengineered using aluminum or 3D-printed composite materials to improve rigidity and expand payload capacity beyond the current 120 g limit.
- The prototype can be extended into an educational robotics kit, with modular assembly and open-source firmware for teaching embedded systems, control theory, and sensor integration in STEM learning environments.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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