IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⪤ Peer-reviewed & Refereed journal ⪤ Vol. 13, Issue 6, June 2026

DOI: 10.17148/IARJSET.2026.13634

Development of a 4-DOF Robotic Arm for Lightweight Precision Automation

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Abstract: As consumer interest in cost-effective and space-efficient automated solutions grows, there is an increasing requirement for versatile robot arms designed specifically for micro-industries and academic settings. The document outlines the creation and implementation of an affordable four-degree-of-freedom robot hand designed specifically for tasks requiring light weight in picking up objects and placing them down. A new design incorporates an integrated mechanical framework constructed of fused elements made from 5 millimeter-thick laser-etched acrylic panels paired with metallic parts for improved stability, longevity, and ease of installation. Integrating high-torque servomotors alongside an ESP32-controlled system enabled highly accurate, consistent, and coordinated movement of joints. Using SolidWorks/Fusion 360 for computer-aided design and kinematic simulation purposes was aimed at verifying the workspace range, power demands, and structural soundness of machinery. This system utilizes pulse-width modulation for precise motor operation through an exclusive controller, facilitating coordinated movement and adaptable scaling capabilities. The experimental assessment showcased dependable management capabilities for objects ranging in weight from 150 grams upwards while maintaining stable positioning precision and optimizing energy usage effectively. A newly engineered robot hand offers economical solutions tailored for lab efficiency, academic studies, and micro-industrial jobs, potentially improving performance via sensors, wireless connections, and smart visual control systems.

1. INTRODUCTION

1.1 Overview

The rapid development of industrial automation and smart manufacturing has accelerated the adoption of robotic systems for specific and repetitive tasks across industries including automotive, electronics, healthcare, and training. Among these systems, robot palms are extensively used due to their high accuracy, repeatability, and capacity to mimic human arm movements.

A robot arm is a programmable manipulator that performs tasks such as pick-and-place, assembly, inspection, and sorting with multiple degrees of freedom (DOF). Specifically,

4-DOF robot arm offers sufficient flexibility for lightweight and medium-precision applications while maintaining simplicity and cost efficiency. Key contributions of this work include:

• Design and simulation of an affordable four-DOF robotic arm using open-source controllers (Arduino/ESP32)

• Development of a compact and scalable platform suitable for laboratory automation and small-scale commercial applications.

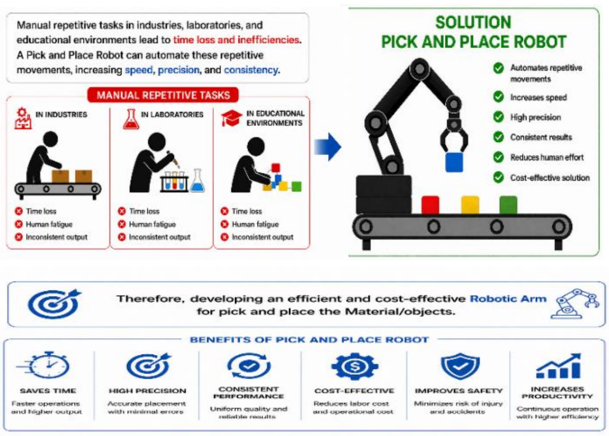

Fig 1.1 Automating Pick and Place Operations.

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1.2 Objective:

• To examine and classify pick-and-place robots mainly based on their mechanical shape and joint configuration.
• To investigate the workspace characteristics and motion capabilities of Cartesian, cylindrical, spherical, articulated, and SCARA robots.
• To identify suitable industrial applications for each robot type based on accuracy, speed, and versatility.
• To understand the advantages and limitations of different mechanical configurations in pick-and-place operations.
• To provide a foundation for selecting the appropriate robot design for automation and material handling applications.
Design a low-cost, programmable 4-DOF robotic arm for pick-and-place operations.
Model, simulate, and validate the system for handling lightweight industrial objects.

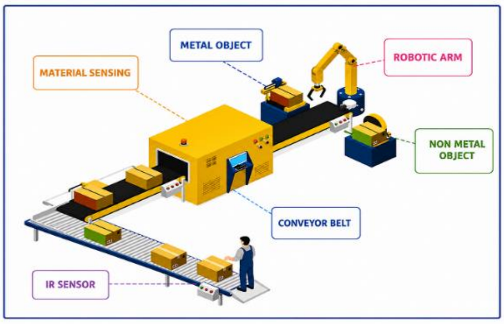

Fig 1.2 Industrial use of Robotic Arms

1.3 Technologies Used in Articulated Robot

1. Designing machinery involves using revolute hinges for flexibility and light-weight components as part of an armature equipped with a grasping mechanism at its tip.
2. Actuation: Servo motors for precise joint control
3.Detection mechanisms include encoders and vision/proximity sensors for measuring positions and identifying objects.
4.Control: Arduino/ESP32-based control using kinematics and PID algorithms
5.Voltage sources like direct current or switching power supplies paired with motor controllers.
6.Programming language: Embedded C/C++. Additional software includes CAD systems like SolidWorks and Fusion 360 for simulations.
7.Communication: Serial, I2C, Wi-Fi, or Bluetooth
8.Safety: Limit switches and emergency stop mechanisms.

2. METHODOLOGY

1. Literature Survey
2. CAD Modeling in SolidWorks
3. DOF Analysis & Component Selection
4. Kinematic Simulation & Motion Analysis
5. Hardware Assembly
6. Programing & Control Logic Development
7. Testing
8. Optimization & Final Validation

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3. WORKING PRINCIPLE

The working can be explained in the following stages:

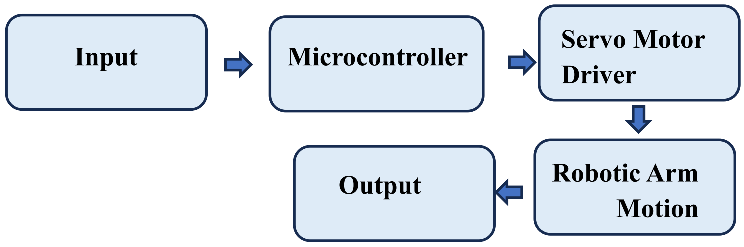
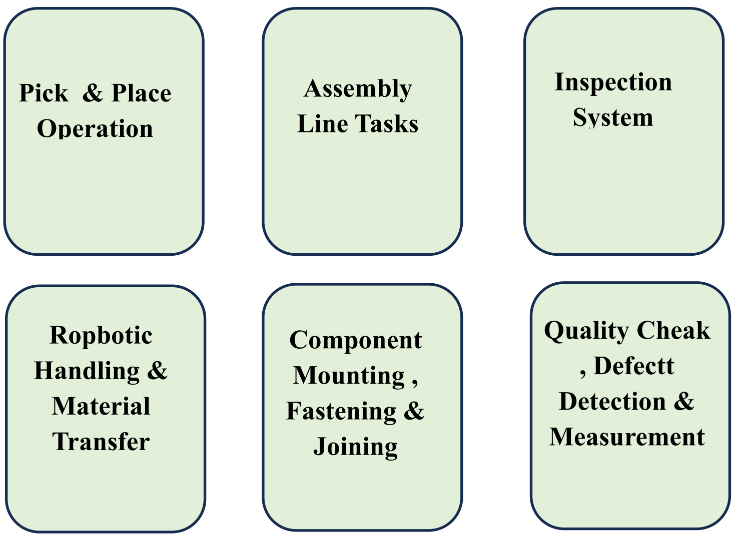


Fig 1.3 Block Diagram Of Working Principal

The4-DOF robotic arm works by controlling servo motors at the base, shoulder, elbow, and gripper joints in a coordinated way. When the system is turned on, the microcontroller resets all the servos to their starting position. Input from the user or programmed instructions is turned into PWM signals, which make each servo move to the correct angle. The movement of each joint is carefully timed to allow the arm to pick up and place objects accurately. The system uses set delays or sensor input to keep the arm's position precise and safe. Once the task is done, the arm goes back to its starting position, making sure it works the same way every time. Overall, the system is an electromechanical device that combines a mechanical frame, motor control, and a computer system to handle small objects automatically and with precision.

4. CONCEPTUAL APPLICATION

The proposed 4-DOF robotic arm is a light, affordable, and easy-to-program system that works well for automation and teaching. It has a flexible design that makes it easy to use in various settings like:
• Moving small parts in small factories
• Putting things together, sorting items, and packing light components
• Checking things with built-in sensors or cameras
The arm can work non-stop with high precision, which helps cut down on manual work and boosts efficiency.



5. APPLICATIONS IN INDUSTRIAL AUTOMATION

The suggested 4DOF robotic arm is ideal for various industrial automation tasks that need precision, consistency, and affordability.
- Pick-and-place operations: It allows for accurate and reliable movement of light-weight parts between work areas, storage bins, or conveyor belts, cutting down on manual work and speeding up the process.
- Assembly line tasks:
it can secure components with precision using controlled joints, helping to maintain a high standard of product quality.

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- Sorting and packaging: It can sort and arrange items based on sensor data like size or color, making manufacturing and logistics faster and more dependable.
- Inspection and quality control: It can use sensors or cameras to detect flaws and check dimensions or appearance, reducing mistakes made by humans.
- Continuous operation: It can run 24 hours a day with steady precision, boosting output and cutting down on running costs.

Industrial benefits include better accuracy and consistency, safer working conditions, higher production rates, fewer errors, and affordable automation options for smaller businesses.

6. CLASSIFICATION OF PICK-AND-PLACE ROBOTS BASED ON MECHANICAL STRUCTURE

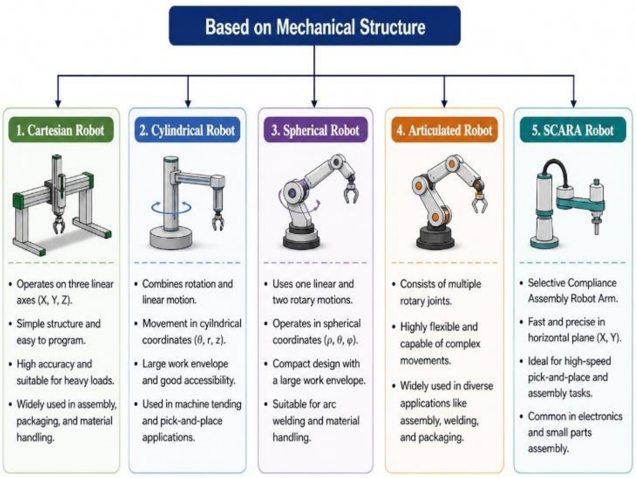

Fig 1.5 Classification Of mechanical Robots

Pick-and-place robots are classified based on their mechanical structure and joint configuration, which determine workspace and motion capability.

• Cartesian Robot: Uses three straight movement directions (X, Y, Z) to offer precise control and easy operation for tasks like packaging and moving materials.

• Cylindrical Robot: Moves in both rotating and straight lines, creating a circular workspace that's good for loading machines and putting things together.

• Spherical (Polar) Robot: Uses turning and straight movements to cover a large, round area, making it useful for welding and handling items.

• Articulated Robot: Has several rotating joints that allow it to move in many ways, making it perfect for complicated tasks like picking up and placing objects or assembling parts.

• SCARA Robot: Moves quickly and accurately in a flat plane with strong support upwards, commonly used for fast picking and placing and assembling electronic parts.

7. DESIGN OF FRAME (LASER-CUT ACRYLIC AND ALUMINUM STRUCTURE)

Almost all joints, motors, and electronic parts are supported by the 4-Degree-of-Freedom (4-DOF) robotic arm's frame. The design is robust, precise, and lightweight to facilitate smooth and precise picking/positioning. The frame is made from a combination of laser-cut 5 mm acrylic sheets and aluminum parts to ensure its strength and affordability.

• Key Design Features:
By utilizing laser-cut acrylic and aluminums for strength, the frame enhances its weight and stiffness. By utilizing CAD software like SolidWorks or FusioThe360, the size of this design was determined in relation to both torque and weight. By using laser cutting, the part shapes were honed to perfection, resulting in consistent and reliable parts.

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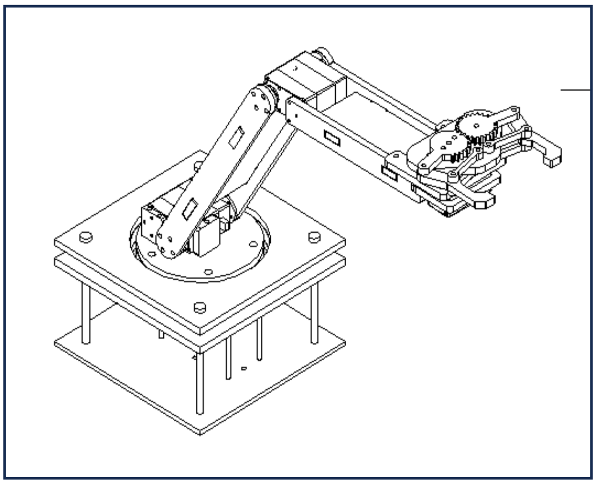
• Fabrication and Assembly.
A laser was used to cut the acrylic parts and aluminum brackets were used for the areas where tension is most likely to occur. The assembly involved the use of standard screws and bolts to ensure proper alignment and a strong attachment. We calibrated the arm to ensure precise movement in all four directions after assembling it.
• Performance Observations.
Despite carrying a 200-gram load, the arm operates smoothly and with confidence without deformity. The servos' lightweight design helps to minimize power consumption and heat. This is an added benefit.

• Testing and Calibration.
The control program can be transferred to the ESP32 using a USB cable. The serial output of the Arduino IDE is used to calyptrate each servo's starting position. Examine each joint's motion separately before employing the entire arm.

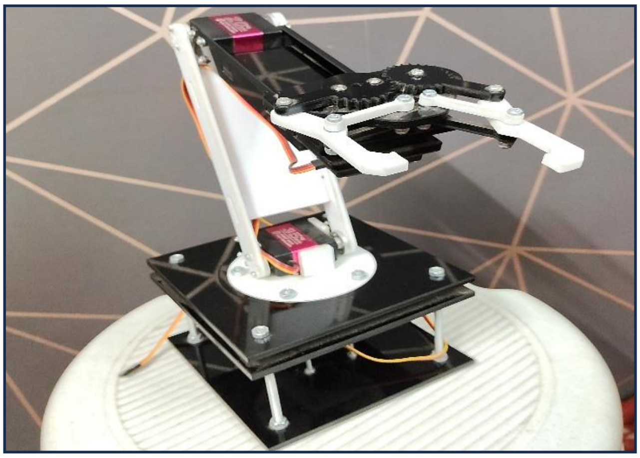
• Final Integration.
The ESP32, motor driver, and power converter are among the electronics that can be mounted on a small acrylic or 3D printed base. Make sure that the wires are secured and don't hinder any moving parts. Make a final assessment to ensure that all four degrees of freedom are moving in the same direction.

• Safety and Finishing.
All exposed wire ends should be covered with heat-shrink tubing or electrical tape. Establish a sufficient air circulation around the power supply and converter modules. Avoid loose screws by using thread lock to prevent them from moving or vibrating.

8.1 3D MODEL ASSEMBLY



8.2 ACTUAL MODEL IMAGES



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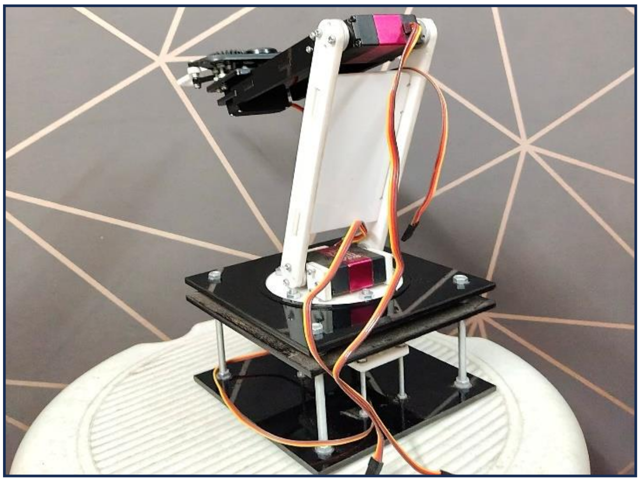

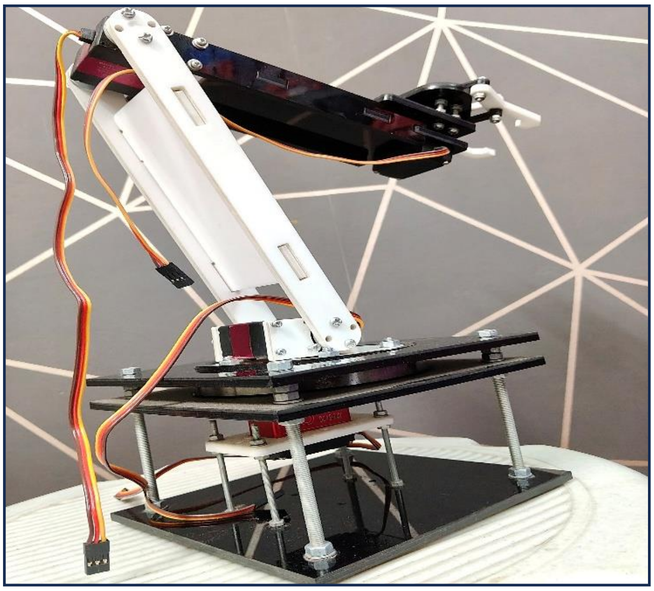

9. LITERATURE REVIEW

9.1 History of robot Technology

The history of robotic technology traces back to significant advancements during the middle part of the twentieth century. The incorporation of intelligent automated machines capable of executing tasks automatically in industries involving routine and dangerous production processes.
Assignments. Earlier models showcased successful applications within automotive manufacturing processes, laying down groundwork for future developments.
The cornerstone of contemporary automated manufacturing systems. Improvements in microchips technology, precise motor regulation systems, and cutting-edge programming techniques have been instrumental.
During the 1970s and 1980s, sensing technologies advanced, leading to the development of more sophisticated multi-axis manipulators.
Accuracy and adaptability. In the late '90s, robots began appearing in healthcare settings, educational institutions, and outer-space exploration projects.
Software programs. Over the past few decades, inexpensive microprocessors and budget-friendly mechanisms have become more accessible.
Accessibility is enhanced by contemporary setups which incorporate features such as sight technology, AI applications, and Internet of Things innovations.
Recent studies focus on creating compact yet versatile structures at lower costs.

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CONCLUSION

The developed 4-DOF robotic arm successfully achieved its objective of automating pick-and-place operations with good accuracy and reliability. The integration of ESP32, high-torque servo motors, and a lightweight acrylic–aluminum structure resulted in smooth and coordinated movement of all joints. Experimental testing demonstrated stable operation, satisfactory payload handling, and repeatable performance for lightweight objects. The system is cost-effective, easy to program, and suitable for educational, research, and small-scale industrial applications. Furthermore, the modular design allows future enhancements such as wireless control, sensor integration, computer vision, and AI-based automation, making the robotic arm a flexible and scalable solution for modern robotic applications.

REFERENCES

[1]. Pick and Place Planning is Better than Pick Planning then Place Planning Shanthi and Hermans (IEEE RA-L, 2024) proposed a joint pick-and-place planning approach that improves accuracy in cluttered environments.
Research Gap: High computational demand, limited robustness to real-world uncertainties, poor adaptability to diverse objects, and lack of energy or cycle-time optimization.

[2]. Visual-Based Pick and Place 6-DOF Robot Manipulator Wijaya et al. (JAEE, 2024) developed a vision-controlled 6-DOF robotic arm for pick-and-place tasks.
Research Gap: Sensitivity to lighting, limited speed optimization, weak performance under occlusion, and restriction to simple object geometries.

[3]. AI-Based Pick-and-Place System Using 2D and 3D Vision Sensors Huda et al. (Machines, 2024) presented an AI-driven system achieving high detection accuracy using 2D/3D vision.
Research Gap: High hardware cost, heavy computational load, environmental sensitivity, and limited focus on low-cost embedded platforms.

[4]. A Large-Reach Manipulator for Planetary Cave Exploration Zivkov et al. (arXiv, 2024) introduced a long-reach manipulator for low-gravity exploration.
Research Gap: Structural complexity, high energy consumption, lack of fine manipulation capability, and limited Earth-based validation.

[5]. Pick and Place Robotic Arm: A Review Paper
Pawar et al. (IJARSCT, 2025) reviewed industrial pick-and-place robotic systems and emerging trends.
Research Gap: High system cost, limited environmental adaptability, immature AI integration, and poor scalability beyond prototypes.

[6]. Design and Implementation of Pick and Place Robotic Arm Using Arduino
Ramadhan et al. (IJSR, 2022) developed an Arduino-based robotic arm for lightweight object handling.
Research Gap: Limited degrees of freedom, low payload capacity, absence of intelligent control, and lack of industrial validation.