



Design and Construction of Five Axis Robotic Manipulator

Dr . Ganesh Yadav

Department of mechanical engineering
Tulsiramji Gaikwad-Patil College of Engineering &
Technology, Nagpur, Maharashtra, India

Email: ganesh.mechanical@tgpcet.com

ORCID ID :-0000-0002-0184-3777

Samek B. Moon

Department of mechanical
engineering
Tulsiramji Gaikwad-Patil College of
Engineering & Technology, Nagpur,
Maharashtra, India

Email:

samekmoon2004@gmail.com

Om S. Ingale

Department of mechanical
engineering
Tulsiramji Gaikwad-Patil College
of Engineering & Technology,
Nagpur, Maharashtra, India

Email: ingaleo610@gmail.com

Sanjaydeep R. Chahande

Department of mechanical engineering
Tulsiramji Gaikwad-Patil College of Engineering &
Technology, Nagpur, Maharashtra, India

Email :- chahandesanjay733@gmail.com

Om N. Zade

Department of mechanical
engineering
Tulsiramji Gaikwad-Patil College of
Engineering & Technology, Nagpur,
Maharashtra, India

Email: omzade9960@gmail.com

Yash Dhawane

Department of mechanical
engineering
Tulsiramji Gaikwad-Patil College
of Engineering & Technology,
Nagpur, Maharashtra, India

Email :-

yashdhawane5@gmail.com

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ABSTRACT

A robotic arm is an artificial limb designed to execute designated tasks. Currently, there is an increasing demand to develop artificial arms for various non-human applications where direct human involvement is impractical. Since humans perform object manipulation intuitively without deliberate consideration of procedural steps, robotic arms are controlled through both wired and wireless mechanisms. This paper addresses the design and angular control of a robotic arm utilizing a Cortex ARM M3 LPC1768 Microcontroller, integrated with an ultrasonic sensor and a computer-based digital controller. The robotic arm operates with five Degrees of Freedom (DoF), with a servo motor positioned at each joint. Each servo motor functions to regulate link positioning through microcontroller-based control, enabling the robotic arm to orient links at specified

angles. Angular feedback is obtained through rotary-encoder measurement. This paper aims to demonstrate how intelligent automation can be implemented in industrial settings to minimize human error, improve product quality, and accelerate manufacturing and processing operations. A primary advantage of robotic arms is their capability to operate in hazardous environments, including high temperature and pressure conditions unsuitable for human workers. Robotic arms offer flexibility for updates and modifications. Additionally, robotic arms reduce overall operational costs and mitigate worker injury risks. The designed robotic arm's performance has been experimentally validated, with simulation results presented and analyzed.



I. INTRODUCTION

Robotics has emerged as a critical component in contemporary manufacturing, automation, education, and research domains. Robotic manipulators are extensively employed for repetitive operations including material handling, assembly, sorting, inspection, and pick-and-place applications. A robotic arm comprises interconnected links and joints that facilitate controlled motion of an end effector. The degree of freedom of a robotic manipulator denotes the quantity of independent movements necessary to establish its configuration. A five-degree-of-freedom robotic arm incorporates five independently controlled joint motions, enabling the end effector to achieve an extensive array of positions and orientations throughout its operational workspace. The proposed initiative concentrates on the engineering and construction of an automated 5-DOF robotic arm apparatus utilizing readily obtainable mechanical elements, drive systems, and digital control infrastructure. The aim is to establish a lightweight and cost-effective robotic platform that exhibits synchronized movement across multiple articulations. This system serves as both an instructional and investigative instrument for examining robotic mechanisms, kinematic principles, actuator regulation, and mechanized processes. The development of multi-DOF manipulators necessitates evaluation of mechanical configuration, actuator force capacity, articulation geometry, operational envelope, load capacity, command methodology, and structural integrity. Authoritative robotics scholarship furnishes analytical frameworks for forward and inverse kinematics, motion path planning, structural engineering, and manipulation control [1]–[3]. Existing literature on 5-DOF robotic arms has further illustrated the implementation of Denavit-Hartenberg parameters and kinematic examination in robotic-arm development [4], [5].

II. LITERATURE REVIEW

Craig established foundational approaches for robotic manipulator modeling, encompassing spatial transformations, forward and inverse kinematics, Jacobians, dynamics, trajectory planning, mechanical design, and robot programming [1]. These foundational concepts serve as the theoretical basis for constructing multi-degree-of-freedom robotic manipulators. Siciliano et al. examined robotic modeling, planning, control, actuators, sensors, trajectory planning, and motion control [2]. Their research illustrates that effective robotic manipulation necessitates the integration of mechanical design with sensing and control systems. Spong, Hutchinson, and Vidyasagar offered an extensive analysis of robot modeling and control, addressing mathematical modeling and control methodologies for robotic manipulators [3]. Narayan et al. described the design and kinematic analysis of a 5-DOF robotic arm equipped with a three-fingered gripper. The investigation employed Denavit-Hartenberg parameters to conduct forward, inverse, and velocity kinematic analysis and presented trajectory-based analysis of the robotic arm [4]. Shrey et al. examined the forward kinematic analysis of a 5-DOF LYNX6 robotic

arm and utilized Denavit-Hartenberg parameters to evaluate the manipulator's kinematic behavior and workspace [5]. Optimization of lightweight 5-DOF robotic arms has been explored for applications demanding reduced mass, enhanced energy efficiency, and adequate mechanical performance. These investigations underscore the significance of determining appropriate joint configurations, actuators, gearing systems, and structural parameters [6]. The examined literature demonstrates that an operational 5-DOF robotic arm demands integrated consideration of mechanical design, actuator selection, kinematic modeling, control systems, and fabrication processes.

III. PROBLEM STATEMENT

Conventional manual material handling and repetitive positioning operations demand sustained human involvement and frequently produce inconsistent results when executed repeatedly. Industrial robotic systems possess the capability to automate such operations; however, they often prove prohibitively expensive and overly complex for small-scale applications and educational laboratory environments. Consequently, there exists a necessity to develop a compact, cost-effective, and user-friendly robotic arm capable of demonstrating automated multi-axis movement and fundamental material handling capabilities. The proposed initiative addresses this necessity through the design and construction of an automated 5-degree-of-freedom robotic arm mechanism.

IV. OBJECTIVES

The primary objectives of the proposed undertaking are:

1. To design a five-degree-of-freedom robotic arm mechanism.
2. To fabricate the mechanical links and supporting structure of the robotic arm.
3. To provide independent actuation for the five joints.
4. To develop a microcontroller-based control system for coordinated joint movement.
5. To analyze the fundamental kinematics of the robotic arm.
6. To develop an end effector capable of gripping and handling lightweight objects.
7. To demonstrate automated positioning and pick-and-place operations.
8. To develop a low-cost experimental platform for studying robotic automation.

V. PROPOSED SYSTEM

The proposed robotic system comprises five primary rotational joints interconnected via mechanical linkages. The base joint facilitates rotational movement of the arm along the vertical axis. The shoulder and elbow joints enable the primary positioning functionality of the arm, whereas the wrist joints facilitate supplementary orientation of the end effector. A standard system architecture includes: Input/Control → Microcontroller → Servo/Actuator Drivers → Five Joint Actuators → Robotic Links → End Effector. The microcontroller processes control commands and



produces appropriate signals for the actuators. Each joint receives an individual control variable assignment. Through coordinated joint movements, the end effector can be positioned to a target location within the operational workspace.

VI. MECHANICAL DESIGN

The mechanical framework incorporates a stationary base, articulated joints, arm segments, wrist assembly, and end effector. Link dimensions must be determined based on the required workspace, actuator torque capacity, payload specifications, and material availability. The principal mechanical components include:

- Base plate and rotating platform
- Shoulder link
- Upper-arm link
- Forearm link
- Wrist links
- Joint brackets
- Servo-motor mounting configurations
- End-effector/gripper
- Fasteners and connecting elements

The structure must maintain sufficient rigidity to minimize undesired vibration and deflection during operation. Lightweight design reduces actuator torque demands, while adequate stiffness is essential for preserving positioning precision.

VII. ACTUATION AND CONTROL SYSTEM

Servo motors serve as suitable actuators for the five joints, as they deliver position control and demonstrate relative simplicity in microcontroller integration. Each actuator connects to a dedicated joint. An Arduino-class microcontroller may function as the primary control unit. The controller generates pulse-width modulation (PWM) signals that correspond to the required angular positions of the servo motors. The fundamental control sequence is:

1. Initialize the controller and actuators.
2. Establish the initial position of each joint.
3. Obtain the desired joint positions.
4. Formulate corresponding actuator commands.
5. Direct the joints toward their commanded positions.
6. Synchronize the joints to position the end effector.
7. Activate the gripper as necessary.
8. Restore the arm to a predefined position upon task completion.

The specifications of the actual controller and actuators shall be documented in accordance with the components integrated into the fabricated prototype.

VIII. KINEMATIC ANALYSIS

Kinematic analysis establishes the relationship between joint variables and the position and orientation of the end effector. In a multi-joint robotic arm, forward kinematics calculates the end-effector pose from known joint angles, whereas inverse kinematics determines appropriate joint angles for an intended end-effector pose. The Denavit-Hartenberg (D-H) convention offers a systematic approach for characterizing the geometric relationship between consecutive links [7].

Each link is characterized by four parameters:

- Link length, (a_i)
- Link twist, (α_i)
- Link offset, (d_i)

- Joint angle, (θ_i)

The homogeneous transformation matrix between two consecutive coordinate frames can be expressed as

$$[{}^{i-1}T_i] = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For a 5-degree-of-freedom manipulator, the complete transformation can be formulated as $[{}^0T_5]$

The resulting matrix characterizes the position and orientation of the end effector relative to the base coordinate frame. The D-H parameter table must be derived from the actual dimensions and joint configuration of the fabricated prototype rather than relying on assumed dimensions that may not correspond to the physical model[8].

IX. FABRICATION METHODOLOGY

The fabrication process commences with the development of the mechanical design and the identification of appropriate materials. The individual links and mounting brackets are produced in accordance with the established dimensions. Provisions are made for holes and mounting features to accommodate servo motors and connecting fasteners. The principal fabrication stages comprise: Design → Material Selection → Component Manufacturing → Joint Assembly → Actuator Mounting → Electrical Wiring → Controller Programming → Testing Following fabrication, the links are integrated sequentially from the base toward the end effector. The actuators are positioned at their designated joints and mechanically connected to the links. The electronic control system is subsequently connected and configured. The assembled robotic arm undergoes testing for individual joint movement initially. Upon confirmation of individual joint functionality, multiple joints are activated concurrently to assess coordinated motion.[9].

X. WORKING PRINCIPLE

The robotic arm functions by converting electrical control signals into mechanical rotational motion via servo actuators. The microcontroller transmits position commands to the actuators. Each actuator rotates its corresponding joint to a designated angular position. The collective motion of the five joints modifies the position and orientation of the end effector. Throughout a pick-and-place operation, the arm initially advances toward the object, the gripper secures the object, and the arm proceeds to the target location. The gripper subsequently releases the object. The sequence may be expressed as: Home Position → Move to Object → Lower Arm → Close Gripper → Lift Object → Move to Target → Re[10].

XI. EXPERIMENTAL TESTING

The constructed prototype must undergo comprehensive practical evaluation through a systematic testing regimen. Initial assessment involves isolated joint testing to confirm



the rotational capability of each actuator. Subsequently, multi-joint testing is executed to assess synchronized operational movement. The following measurable parameters should be documented during the experimental phase:

- Joint angular range
- End-effector positioning error

- Repeatability
- Payload capacity
- Operating time
- Power consumption
- Gripping performance
- Workspace
- Smoothness of motion

XII. RESULTS AND DISCUSSION

The constructed robotic arm is anticipated to exhibit autonomous and synchronized movement across all five joints. Individual joint testing serves to validate that each actuator responds appropriately to the specified programmed instructions. Synchronized motion can subsequently be assessed through predetermined pick-and-place operational sequences. The robotic arm's operational performance is contingent upon multiple variables, encompassing link geometry, structural stability, actuator torque capacity, electrical power supply, joint backlash magnitude, payload specifications, controller precision, and mechanical alignment accuracy.[11] For the comprehensive experimental documentation, quantitative measurements must be recorded for positioning accuracy, repeatability, payload capacity, operational workspace, and cycle duration. These empirical measurements will furnish an objective assessment of the constructed prototype's performance. The kinematic model may be validated by comparison with experimentally determined end-effector positions. The deviation between theoretically calculated and experimentally measured positions can be quantified as positioning error:
$$E = \sqrt{(x_c - x_m)^2 + (y_c - y_m)^2 + (z_c - z_m)^2}$$
 where (x_c, y_c, z_c) denote calculated coordinates and (x_m, y_m, z_m) denote measured coordinates.[12]

XIII. ADVANTAGES

The proposed 5-degree-of-freedom robotic arm offers the following benefits:

- Enables coordinated multi-axis automated motion.

- Appropriate for academic and research laboratory environments.
- Capable of executing repetitive pick-and-place tasks.
- Delivers enhanced operational flexibility compared to single-axis systems.
- Utilizes readily obtainable commercial components for construction[13].
- Serves as an educational platform for robotics and automation studies.
- Accommodates modifications to accommodate various end-effectors and specialized applications.
- Supports integration with sensor systems for advanced automation capabilities.

XIV. LIMITATIONS

The prototype exhibits the following constraints:

- Payload capacity is constrained by actuator torque specifications.
- Mechanical backlash may compromise positioning precision.
- Servo motor performance is limited by maximum speed and torque ratings.
- Operational workspace is determined by link geometry and permissible joint ranges.
- Open-loop control architecture cannot address external disturbances effectively.
- Multiple actuators necessitate a dedicated regulated power supply unit.
- Industrial-scale applications require substantial mechanical and control system enhancements before deployment[14].

XV. APPLICATIONS

The developed robotic arm is applicable to:

- Pick-and-place operations
- Academic robotics laboratory environments
- Compact-scale material handling tasks
- Object classification and sorting
- Robotic kinematics demonstration
- Assembly procedure experimentation
- Scientific investigation and technological advancement
- Automated quality inspection procedures
- Prototype-level automation system development

XVI. FUTURE SCOPE

The system can be enhanced further through the incorporation of position feedback mechanisms, force-sensing technology, vision-based systems, wireless connectivity solutions, and sophisticated motion-planning algorithms. A camera-integrated vision system can facilitate the automatic recognition and spatial determination of objects. Implementation of closed-loop control strategies can enhance positioning precision and mitigate the effects of external disturbances[15]. The mechanical framework can be refined through the application of computer-aided design and finite-element analysis methodologies to minimize mass while preserving structural rigidity. Integration of more sophisticated actuators and advanced gear transmission systems may be employed to expand load-bearing capacity. Furthermore, the implementation of trajectory-planning techniques can enable the achievement of more fluid and expedited end-effector motion[16].

XVII. CONCLUSION

This paper has presented the design and manufacturing methodology for an automated five-degree-of-freedom robotic arm assembly. The proposed apparatus combines a multi-articulated mechanical framework, actuation systems, microcontroller-based command architecture, and a terminal effector to facilitate automated multi-axis operational capability[17]. The design methodology is grounded in



established principles of robotic-manipulator engineering, with particular emphasis on kinematic analysis and coordinate system transformation. A five-degree-of-freedom structural configuration delivers substantial adaptability for the positioning and orientation of the end effector throughout the operational workspace[18]. The constructed prototype can function as an economical demonstration platform for illustrating robotic automation principles, kinematic theory, actuator management, and material-handling operations[19]. To achieve comprehensive experimental documentation suitable for publication, quantitative performance metrics obtained from the physical prototype should be incorporated to substantiate the mechanical and control system design through empirical validation[20].

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