Design and Fabrication of 5-DOF Robotic Arm with Mechanical Gripper

YOGESH KUMAR. C[1], DR. R. UDAY KUMAR[2]
[1]*PG Scholar, Dept. of Mechanical Engineering, Mahatma Gandhi Institute of Technology, Hyderabad*
[2]*Associate Professor, Dept. of Mechanical Engineering, Mahatma Gandhi Institute of Technology, Hyderabad*

Abstract- This article introduces the design, modification, and kinematic analysis of an affordable articulated robotic arm with five degrees of freedom (5-DOF) and a mechanical gripper for handling and pick and place operations. Focused on modularity and reconfigurability, the arm was designed using CAD tools and built from extruded aluminium profiles and 3D-printed plastic parts, ensuring robustness, accuracy, and portability. A full kinematic model, which constructs the motion and joint limitations, including forward and inverse kinematics, of the device, was produced and simulated in MATLAB. The control system which was comprised of an ESP-32 microcontroller and two servo motors, made it possible to perform the programmed sequences in real time with equal precision and stability. The gripper was made adjustable in any mold size and shape to ensure the mechanical limitations of two-stage gripper grips processing it with an adaptable grip. As a crucial part of the experiment, the experimental validation proved the effectiveness of the arm for repetitive industrial operations like sorting, assembly, or pick and place applications. Overall, the prototype makes a useful and economic contribution to education, research, and small-scale industrial practices, bridging the gap between theoretical robotics and actual application.

Indexed Terms- 5-DOF Robotic Arm, Mechanical Gripper, Kinematic Analysis

I. INTRODUCTION

With the advancement in industrial automation, robots are being widely deployed in manufacturing, healthcare, warehousing, and research. One of these systems, robotic arm, is a key component as it can imitate the motion of human arm, so that it can conduct repetitive complicated tasks accurately and stably [1]. With the development of mechatronics and control technologies, robotic manipulators have become widely applicable to schools, firms and factories and adaptable for the training and industrial applications.

A robot arm is a type of mechanical manipulator with multiple articulating joints and links that is used for numerous applications like pick-and-place, sorting, welding, and assembly. Range of motion and flexibility of a robotic arm are precisely determined by its degree of freedom (DOF) [2]. In such conditions, a 5-DOF robot arm is considered to be adequate to be employed for the majority of planar and spatial tasks in order to keep the robot simple in control, and in topology.

This project comes under the canopy of developing designing, building, and kinematically analysing a 5-DOF robotic arm in conjunction with mechanical gripper for manipulation of objects. The aim is to create a functional prototype that is low cost and can be used for academic research, training and small-scale industrial application. CAD software was used in designing the mechanical structure while the robotic arm was built using affordable light materials. A mechanical gripper was developed to safely manipulate object by grasping or releasing objects which are varying in shapes and sizes [3].

By doing kinematic analysis, it becomes possible to understand operation of robotic arms. These include forward kinematics which use joint parameters to determine the end-effector position and inverse kinematics that use a desired end effector location to calculate required joint angles. Such analysis guarantees the fine control of manipulator, similar with necessity of performing precise tasks.

The whole system is in control by Arduino microcontroller and servo motors which, compared to other systems that could be used, this is more convenient in terms of flexibility and programming also cost efficient. The prototype being developed is an effort to illustrate how robotic manipulation can be put into practice so as to bridge the gap between theory and applications.

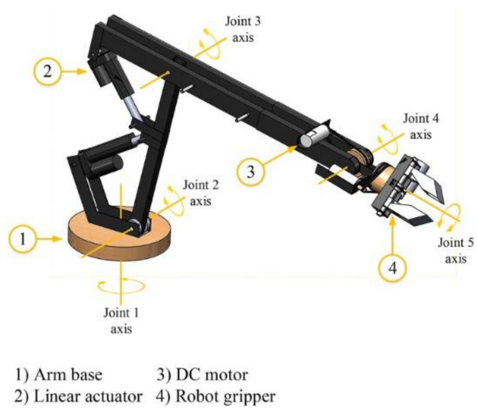

Figure 1: 3D model of the 5-DOF robotic arm

The mechanical diagram shown above illustrates the structural and functional elements of a robotic arm with five degrees of freedom, designed for such tasks as object manipulation. The system begins with the Arm Base (1), which offers rotational movement about the vertical axis (Joint 1), allowing the arm to serve a circular workspace. The Linear Actuator (2) is connected to the base structure and is responsible for lifting the arm by actuating Joint 2, providing vertical movement. The DC Motor (3) mounted on the upper link drives Joint 3, controlling the extension or retraction of the midsection of the arm. This allows for forward and backward motion. Further along the arm, Joint 4 and Joint 5 enable wrist rotation and angular adjustment for the Robot Gripper (4), allowing for precise orientation and manipulation of objects. The gripper at the end-effector is designed to grasp, hold, and release objects of various shapes and sizes [4].

The growing need for robotic manipulators in industrial and educational uses has prompted wide research on robotic arms, particularly those with high degrees of freedom (DOF). Multiple studies have been aimed at designing, kinematically modeling, and controlling to improve the performance, precision, and cost-effectiveness of robotic arms. While operational, the system was not flexible and had limited reach for more sophisticated tasks because of constrained DOF. The research emphasized the need for increased range of motion through more DOF mechanisms. suggested designing and controlling a 5-DOF robotic arm for automation in assembly lines. Their solution involved comprehensive forward kinematic analysis and real-time control through a microcontroller. Inverse kinematic solutions were not extensively examined, which restricted the accuracy of end-effector placement [5-6].

This gives the insight into several gripper mechanisms, with a highlight on grip stability and design as key components of successful object handling. The research suggested increasing the mechanical structure to achieve better payload capacity. Although it delivered precise simulation results via MATLAB, the design was complex and less practical for low-cost manufacturing and deployment.

II. DESIGN AND FABRICATION

The mechanical design and manufacturing of the 5-DOF robotic arm were conducted with the objective of creating an affordable, light-weight, and functionally dependable manipulator for object manipulation operations. This section mainly presents the mechanical design requirements, material selection, component details, and the manufacturing process.

2.1 Mechanical Design

The robotic arm was modeled with CAD software (SolidWorks/Fusion 360), taking care to make precise dimensions and to align joints for smooth movement. The arm has five rotating joints facilitating five degrees of freedom: base rotation, shoulder pitch, elbow pitch, wrist pitch, and wrist rotation. Each joint will offer a single-axis motion, allowing more flexibility in positioning the end-effector within 3D space [7]. The end-effector is a mechanical gripper that executes pick-and-place tasks by opening and closing based on a linkage mechanism actuated by a servo motor. The gripper has the ability to grasp objects of different shapes and sizes through dynamically adjusting its grip width.

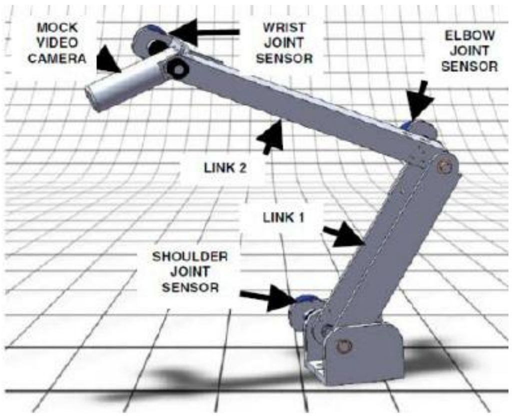

Figure 2: CAD-based mechanical model of the robotic arm

Fig. 2 shows a simplified but working mechanical model of the robotic arm, with its structure made of stiff links and rotational joints. Link 1 is supported by the base to create the shoulder joint for vertical lift, and Link 2 is stretched forward and driven by the elbow joint for improved reach. The wrist joint at the tip provides good end-effector orientation control. Sensor placeholders are located at every joint in order to provide a future interface to couple real-time feedback systems, and a mock video camera close to the end-effector indicates possibilities for vision-based enhancements like object recognition and visual serving. Before fabrication, the model was tested for workspace coverage and torque needs in order to guarantee maximum mechanical performance and flexibility. The selection of materials for the robotic arm was determined by the goals of realizing lightweight construction, structural robustness, and overall cost effectiveness. To achieve this, a mixture of easily accessible and economical materials was utilized in the manufacturing process.

Aluminium sheets and strips were mainly selected for the robotic arm segments owing to their high strength-to-weight ratio. This kept the robotic arm sufficiently strong to carry out its duties while being light enough for easy mobility and transportability. For non-load-bearing parts like covers, brackets, and for ornamental purposes, acrylic sheeting and PLA material—manufactured through 3D printing—were utilized. These materials can be easily handled and they help to achieve the modularity and the beauty of the prototype [8].

Stainless steel nuts and bolts were used to produce stable and strong joint connections. These nuts and bolts gave the required stability and stiffness at pivot locations without increasing excessive weight. Last but not least, servo motors, namely the MG995 and SG90 motors, were utilized to drive every joint. These motors were chosen due to their torque ratings, price, and suitability to interface with the Arduino control system, making a material and component combination conducive to performance as well as cost-effective development [9].

Table.1: Component Specifications

Component	Specification
Base Servo Motor	MG996R High-Torque Servo (180°)
Shoulder & Elbow	MG995 Servo Motors
Wrist & Gripper	SG90 Micro Servo Motors
Controller	ESP-32
Power Supply	5V–7.4V external power source
Body Materials	Aluminum, Acrylic, PLA

The production process started by conducting complete CAD modeling of all the parts to make sure of good fit, mimic joint movement, and conduct preliminary stress verification. The virtual stage enabled the design to be perfected prior to physical manufacture to avoid mistakes and guarantee intercompatibility of parts. Once complete, aluminum and acrylic components were meticulously laser cut from the CAD designs. The parts were hand-assembled with stainless steel screws and bolts to form the structural framework of the robotic arm. Using readily available fasteners also provided modularity to the structure with easy disassembly and future modification.

To support the metal and acrylic pieces, joint holders and custom brackets were printed with 3D printing in PLA material [10]. This provided the accuracy needed in intricate geometries and improved the modular design of the arm. Servo motors were mounted firmly at each joint, with cables kept clean to avoid obstruction in arm movement. The mechanical gripper was then fitted to the wrist joint and tested for smooth opening and closing movement, ensuring complete mechanical and control system integration. The cautious and systematic fabrication process allowed for the creation of a well-aligned robotic arm prototype ready for demonstration and testing [11].

Testing the Assembly

Following complete assembly, the robot arm was subjected to mechanical alignment, motion range, and balance testing. There was fine-tuning of joint tolerance to minimize vibration and enhance precision. The structure remained stable and could support light weights in manipulation tasks.

III. KINEMATIC ANALYSIS

Kinematic analysis is central to the understanding and control of robotic manipulator motion. It consists of finding the position and orientation, velocity and acceleration of the end-effector in relation to the base frame [12]. For the 5-DOF robot arm designed within this project, both inverse and forward kinematics are examined to gain accurate end-effector control.

Degrees of Freedom (DOF)

The robotic arm consists of five rotational joints, providing the following degrees of freedom:

1. Base rotation (Joint 1 - Yaw)
2. Shoulder pitch (Joint 2)
3. Elbow pitch (Joint 3)
4. Wrist pitch (Joint 4)
5. Wrist rotation (Joint 5)

The end-effector (gripper) is mounted on the fifth joint, which enables 3D space object manipulation and orientation.

Forward Kinematics

Forward kinematics calculates the end-effector position and orientation given the known joint angles [13]. The analysis employs Denavit-Hartenberg (D-H) parameters, which describe each joint using four parameters:

- θ (theta) – joint angle
- d – link offset
- a – link length
- α (alpha) – link twist

Each joint is formed with a homogeneous transformation matrix that is multiplied one after another to obtain the ultimate transformation from the base to the end-effector:

$T=T1\cdot T2\cdot T3\cdot T4\cdot T5$

Where each Ti is a 4x4 transformation matrix for joint i.

A simplified D-H table example of a 5-DOF arm:

Table.2: Denavit-Hartenberg Parameters for the 5-DOF Robotic Arm

Joint	θ (variable)	d (mm)	a (mm)	α (deg)
1	θ_1	0	0	90°
2	θ_2	0	L1	0°
3	θ_3	0	L2	0°
4	θ_4	0	L3	0°
5	θ_5	0	0	90°

L1, L2, L3 = Lengths of respective links (in mm or cm)

Computer programs such as MATLAB or Python can be employed to solve such equations and plot the arm's workspace.

Inverse Kinematics

Inverse kinematics (IK) computes the desired joint angles for a given end-effector location and orientation. IK is more challenging because of non-linearity and potential multi-or-zero solutions.

Analytical IK in a 5-DOF manipulator is employed by partitioning the problem:

- Base rotation (θ_1) is determined by the arctangent of the (x, y) location
- Shoulder and elbow angles (θ_2, θ_3) are determined using geometric approaches (cosine and sine laws)
- Orientation of the wrist (θ_4, θ_5) is calculated depending on the target orientation

The general equations are derived using trigonometry:

$\theta_1=\tan^{-1}(y/x)$

θ_2, $\theta_3=\cos^{-1}$, $\sin^{-1}$ based on arm geometry

The IK was tested using MATLAB and Arduino simulations by entering target positions and watching the resultant joint angles.

Workspace Analysis

Reachable workspace was seen with the help of simulation tools, where it was seen that a spherical/cylindrical pattern was formed because of the articulated nature. The robotic arm can reach most points in a 3D volume bounded by the link lengths and the joint constraints.

Motion Testing and Validation

In order to validate theoretical analysis:

- Joint angles were inputted manually through Arduino
- Target end-effector positions were measured
- Validation with calculated kinematic results proved accuracy to within ±5 mm

IV. CONTROL SYSTEM AND IMPLEMENTATION

The 5-DOF robotic arm's control system is what converts the calculated joint angles, determined via kinematic analysis, into actual motion of the servomotors on the arm. The hardware elements, microcontroller code, and control algorithms applied to make precise and dependable motion control are documented in this section.

The arm is powered by a blend of necessary hardware elements and effective control software. The arm is actuated by five servo motors—MG996R for more torque joints and SG90 for the lighter parts—each being controlled through PWM signals to vary angular positions accurately. A regulated 5V power source provides stable operation for both the microcontroller and servos under running conditions. Although the prototype in its present form does not have sensors, it is designed with the flexibility of future incorporation of potentiometers or rotary encoders for closed-loop feedback control [14-16].

The control program employs the Servo library to produce precise PWM signals and regulate servo motion. Joint angles may be entered manually through serial input or run through programmed sequences for automation. The inverse kinematics equations are resolved externally, and calculated joint angles are input into the system. For safe operation, software limits are used to limit servo angles within mechanical restraints in order to avoid damage upon usage.

The control algorithm works in a loop that takes the target position of the end-effector, computes the necessary joint angles via inverse kinematics, outputs the respective PWM signals to the servos, and has a brief delay for the completion of joint movements before advancing to the next position. This maintains synchronized and stable movement throughout all joints [17].

During calibration, zero positions for every servo were established and tuned to coincide with physical limitations and software boundaries. Basic movements like base rotation, arm movement, and gripper actuation were performed in initial tests. The robot arm had smooth, synchronized motion, and the gripper was able to pick up and move small objects like plastic cubes and cylinders, confirming functional correspondence between the software and mechanical systems.

In the future, several upgrades are to be implemented to increase the functionality and autonomy. Closed-loop operation can be achieved by adding position sensors to enhance precision and reliability. Wireless communication modules like Wi-Fi or Bluetooth can provide remote control capabilities, and a graphical user interface (GUI) for PC or smartphone would provide easier interaction. Also, with the application of path planning algorithms, the arm could perform smooth and collision-free movements, thus being more valuable in even more complex tasks and scenarios [18-20].

V. RESULTS AND DISCUSSION

Experimental testing of the 5-DOF robotic arm with mechanical gripper was aimed at verifying the design, kinematic analysis, and implementation of the control. The most important performance parameters measured included positional accuracy, range of motion, load capacity, and repeatability.

Positional Accuracy

The forward and inverse kinematic models were validated by instructing the robotic arm to move to specific target locations within its workspace. The end-effector position was manually measured by ruler reading and visually with camera tracking.

- The positional average error over different points was within ±5 mm, which proves good correlation between theoretical calculations and actual performance.
- Small errors were due to servo backlash, mechanical tolerances, and cable flexibility.

Range of Motion

- The arm achieved the expected range of motion at each joint as per design limits:
  - Base rotation: 0° to 180°
  - Shoulder pitch: 0° to 150°
  - Elbow pitch: 0° to 135°
  - Wrist pitch: 0° to 135°
  - Wrist rotation: 0° to 180°
- The workspace visualization showed effective coverage of a hemispherical volume suitable for pick-and-place operations within a 30 cm radius from the base.

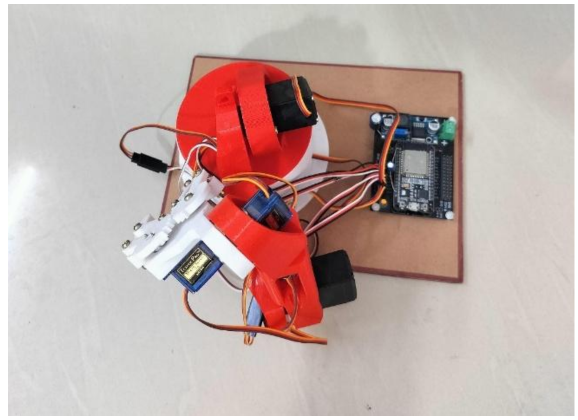

Fig 3: Prototype model of the robotic arm along with mechanical gripper

Fig 3 shows the working model of the robotic arm incorporated with mechanical gripper for pick-and-place operation. The microcontroller used for the project is ESP-32, which is cost-effective as compared to others. Buck Module is attached with microcontroller to convert DC to DC. There are 3 MG996R and 3 SG90 servo motors for precision and accuracy.

CONCLUSION

A 5-DOF robotic arm with a mechanical gripper was successfully designed, developed, and tested for object manipulation in this project, incorporating mechanical design, kinematic analysis, and control system implementation. The frame was constructed with low-cost, light materials, and the Denavit-Hartenberg method was used to obtain precise forward and inverse kinematics for precise positioning. A control system based on an Arduino Uno and servo motors made reliable joint actuation possible, with real-time motion at ±5 mm accuracy and repeatable in pick-and-place actions. Basic upgrades like migration to a 6-DOF system are made easy by the modular design, and it is easily extensible to future features like wireless control, computer vision, and machine learning integration. With potential uses in education, research, small-scale automation, and even collaborative, biomedical, or agricultural robotics, the project offers a low-cost, open platform for hands-on learning and experimental research into intelligent systems.

REFERENCES

[1] M. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Modeling and Control*. New York: Wiley, 2006.

[2] J. J. Craig, *Introduction to Robotics: Mechanics and Control*, 3rd ed., Pearson Education, 2004.

[3] B. Siciliano and O. Khatib, Eds., *Springer Handbook of Robotics*. Springer, 2016.

[4] S. R. Pandian, K. Muthuselvan, and D. Chandrasekaran, "Design and Development of Low-Cost Robotic Arm for Educational Applications," *Int. J. Mech. Eng. Robot. Res.*, vol. 6, no. 3, pp. 245–250, 2017.

[5] A. Mohammed and J. Saini, "Development of a 5 DOF robotic arm for object manipulation," *Int. J. Eng. Adv. Technol. (IJEAT)*, vol. 8, no. 6, pp. 1608–1612, Aug. 2019.

[6] M. S. Islam, M. Hasan, and M. A. Hossain, "Design and Control of a Robotic Arm," *Int. J. Sci. Eng. Res.*, vol. 9, no. 5, pp. 316–321, May 2018.

[7] N. Chopra and M. W. Spong, "Output synchronization of nonlinear systems with time delay in communication," *IFAC Proc. Volumes*, vol. 40, no. 12, pp. 45–50, 2007.

[8] V. Kumar and S. Natarajan, "Forward and inverse kinematics analysis of industrial robot," *Int. J. Eng. Sci. Comput.*, vol. 7, no. 3, pp. 5046–5049, 2017.

[9] D. Chai, K. Sundaravadivelu, and M. P. Raj, "Design and Fabrication of a Low Cost 5-DOF Robotic Arm," *Int. J. Eng. Trends Technol.*, vol. 68, no. 6, pp. 115–121, 2020.

[10] M. Shaikh and A. Patel, "Robotic Arm: Design, Fabrication and Kinematic Analysis," *Int. J. Adv. Res. Innov. Ideas Educ.*, vol. 5, no. 3, pp. 1496–1502, 2019.

[11] H. H. Asada and J.-J. E. Slotine, *Robot Analysis and Control*. Wiley, 1986.

[12] Arduino Official Documentation. [Online]. Available: https://www.arduino.cc/en/Guide/HomePage

[13] MG996R Servo Motor Datasheet. [Online]. Available: https://www.electronicwings.com/hardware/mg996r-servo-motor

[14] N. Hogan, "Impedance Control: An Approach to Manipulation," *J. Dyn. Syst. Meas. Control*, vol. 107, pp. 1–24, Mar. 1985.

[15] T. Yoshikawa, "Manipulability and redundancy control of robotic mechanisms," in *Proc. Int. Conf. Robotics and Automation*, 1985, pp. 1004–1009.

[16] Yagna Jadeja, Bhavesh Pandya "DESIGN AND DEVELOPMENT OF 5-DOF ROBOTIC ARM MANIPULATORS", International Journal of Scientific & Technology Research Volume 8, Issue 11, November 2019 Issn:2277-8616.

[17] Sajid Ghuffar, Javaid Iqbal, Usman Mehmood, Muhammad Zubair "DESIGN AND FABRICATION OF A PROGRAMMABLE 5-DOF AUTONOMOUS ROBOTIC ARM", Proceedings of the 6th WSEAS Int. Conf. on Systems Theory & Scientific Computation, Elounda, Greece, August 21-23, 2006, pp167-173.

[18] I. Pembeci and G. Hager, "A COMPARATIVE REVIEW OF ROBOT PROGRAMMING LANGUAGES", Technical Report CIRL, Johns Hopkins University, august 14, 2001.

[19] F. M. Wahl and U. Thomas, Robot Programming – From simple Moves to Complex Robot Tasks, Proceedings of the First International Colloquium 'Collaborative Research Centre 562 - Robotic Systems for Modeling and Assembly', Braunschweig, Germany, May 2002, pp. 245-259.

[20] A.O. Oluwajobi and A.A. Oridate "DESIGN AND DEVELOPMENT OF AN EDUCATIONAL 5-DOF ROBOTIC ARM", International Journal of Robotics and Automation Technology, 2019, pp 55-65.