Design & Implementation Of a 5DOF Pick&Place Robotic Arm

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Abstract:

This paper describes the design and implementation of a highly optimized 5-DOF robotic arm for cost-effectiveness, ease of use, and precise pick-and-place operations. The key feature of the robotic arm designed here was to be a very affordable and performance-oriented device using high-torque actuators for smooth, accurate joint motion. Its structure was designed on CAD software and fabricated in 3D printing, thus amenable to easy customization as well as lower production costs. By implementing a forward kinematics algorithm through the Denavit-Hartenberg parameter method, the location and orientation of the end-effector can be accurately established.The graphical user interface developed is intuitive, allowing for control methods and automation. For serial communication of the control system, information communication is easier in order to ensure operation is smooth. This will hence be able to express a practical approach towards making robotic arms affordable, highly accurate, and user-friendly for multiple applications such as industrial automation and research platforms. With accessible fabrication techniques and robust control methods, the system presents a balanced solution for users who seek efficient and customisable robotic systems.

Keywords: Robotic arm, Forward Kinematics,DH parameters, GUI, Inverse Kinematics,Serial Communication.

1. Introduction:

The history of robotics started when, in the year 1954, George Devol invented the first industrial robot. Since then, development in robotics has been vast and wide-ranging. In the last few decades, it has achieved immense progress. Today, robots have become unavoidable in many industries and transformed the industrial landscape of the world. From assembling parts to packaging, it is utilised on shop floors for the assembly of various components. In healthcare, surgical procedures demanding precision and complexity have been performed using robots. These impacts are obvious as robotics increasingly serves human activities in many areas, be it in its efficiency or safety.

Robotic arms especially replicate the dexterity and precision of the human arm, which makes them indispensable in repetitive tasks as well as hazardous ones. Designing robots for different applications varies considerably. While humanoid robots are designed to mimic human form and behavior and emphasise natural interactions, robots that are designed for healthcare have placed emphasis on precision, reliability, and safety in medical procedures.

In this paper, we discuss our findings on designing and developing a 5-DOF robotic arm with cost-effectiveness, ease of use, and precise control. The main goal of our research work is to design a strong and efficient robotic arm that will pick and place items with high precision and reliability.

2. Related Work:

The paper[1] explores the simulation results of 1DOF clutched robotic arm; his work on a unique mechanical design with clutches where the arm makes use of just one motor to generate multiple 3D modes of motion. The proposed system makes use of a clutch-gearing mechanism that is either activatable or deactivatable, for various rotational motions.Recently there were new robotic arms in SOPHIA[2] and ATLAS[3]. They operate rather smoothly, flexibly, and almost human-like, but they are also pretty expensive and complicated systems not for any non-professional end-users.

Today, for humanoid and service robots arms are still key parts, and they need to be more anthropomorphic, low energy consumption and safe. To these purposes, many researchers developed designs for anthropomorphic arms like, for example, in [4], [5].

In[6]discusses the development and implementation of a miniature robotic arm that can control a larger robotic arm with three degrees of freedom. In[7]author utilised accelerometers, the components of the acceleration parallel to the assumed axes (X, Y, Z) have relation among themselves with the total magnitude. angles, velocity are obtained accurately.

In this[8]author discusses the design and path planning of a robotic arm designed for inspection of pipelines, more appropriately to pipeline inspection environments, requires detection of obstacles and avoiding obstacles while carrying out detailed inspections.In [8.1] discusses about 2-axis and 3-axis robot manipulators ,in [9] 4-axis, in [10] 5-axis, in [11] 6-axis.

In[12] author discusses the design and development of a 6DOF, known as PC-ROBOARM. Here, he considers the arm to be a three-link system wherein every joint is linked with a servomotor. The authors also introduce some software known as SMART ARM(GUI) which helps in the design, simulation, and control of the robotic arm.

In[13] author discusses the explored the performance of a plywood-based 5 DOF robotic arm controlled through a Smartphone GUI via Bluetooth. While functional, their system showed significant inaccuracies (>25% of error) in basic drawing tasks, primarily due to unpowered actuators and open-loop control.

Our Design addresses these limitations by (1) employing high torque NEMA17 stepper motors for major joints and precision SG90 servo motors for end-effector control, (2) Implementing both Inverse and forward Kinematics for improved accuracy, and (3) replacing smartphone control with the Python based GUI.

In[14] another research of a 5-DOF robotic arm for lightweight industrial tasks in Pakistan, using Finite Element Analysis to optimize strength and payload capacity. While their design relied on servos and Arduino control for basic material handling we have improved upon this approach by blending high torque stepper motor with precision servo enhancing both power and accuracy.

3. SYSTEM DESIGN AND ARCHITECTURE:

This robot is having there NEMA17 Stepper motors at BASE,SHOULDER, ELBOW for higher torques and two SG90 servos at WRIST and GRIPPER for precise angular adjustments to facilitate controlled movements and precision across all joints . Designed a 3D CAD model of our robotic arm using SOLID WORKS[15] and we utilised 3D printer[16] to print all parts of the robot. In the control system, it will be the simplest and most cost-effective way by choosing the AryaBhatta 805MicroController. MicroController will get Commands from our Graphical user Interface(GUI) and performs the actions on the actuators. Table1 Shows the torque, range and operating voltages of the actuators used in this project.

Table1: Specifications of the Motors(author)

JOINT	ACTUATOR	TORQUE/ STEP ANGLE	RANGE	VOLTAGE
BASE	NEMA 17(Metal Gear)	4 Kg-cm/ 1.8	∓360	12V[14.1]
SHOULDER	NEMA 17(Metal Gear)	4 Kg-cm/ 1.8	-3 to +183	12V[14.1]
ELBOW	NEMA 17(Metal Gear)	4 Kg-cm/ 1.8	∓360	12V[14.1]
WRIST	SG90(Plastic Gear)	1.2kg-cm	0 to 180	3.0V~ 7.2V[14.2]
GRIPPER	SG90(Plastic Gear)	1.2kg-cm	0 to 180	3.0V~ 7.2V[14.2]

In fig1 the design flow of the robot is shown and then developed a Graphical user Interface using Python known as FlexArm5X.From this interface 8051µC will receive Comands using serial communication UART cable, and move the motors angles according to the commands received.

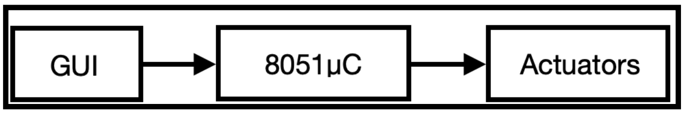

Fig1 design flow of the Robot (design by author)

4. Methodology:

"In mechanical systems study, it is always important to understand the motion of its different components. This is what defines kinematics: Kinematics is the study of motion of mechanical points, bodies and systems with due consideration of their own physical properties as well as forces acting on them. This basic concept makes engineers and scientists analyze motion systematically and not incorporate displacement, velocity, and acceleration." Finding Position and orientation of the end effector at the given joint angles is known as Forward Kinematics[17] the common way to implement forward kinematic is by using Denavit-Hartenberg (DH)[18] parameterization a mathematical technique. first we build a free body diagram of the robotic arm With this then we define coordinate frames at every joint, each frame is defined by four parameters known as DH parameters(link length (a_i),link twist(α_i),joint offset(d_i) and joint angle(θi) . The we will apply the Generic Link-Coordinate Transformation Matrix from Base to End Effector.fig2 shows the Free Body diagram of the robot.

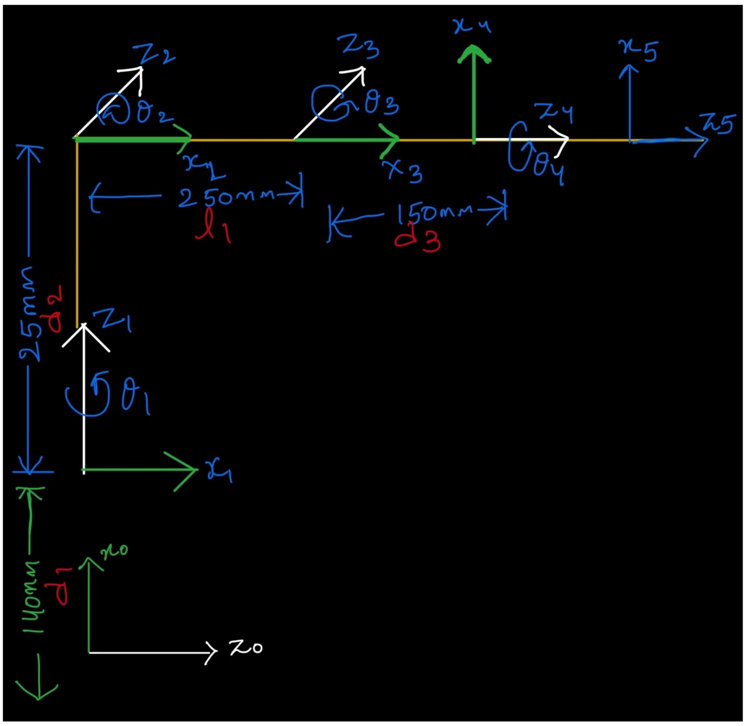

Fig2 Free Body Diagram of the 5DOF robot

With help of MATLAB library DH table Solver[19] forward kinematic is solved for the robot, this library takes DH parameters link length (ai),link twist(αi),joint offset(di) and joint angle(θi) as input and solves all the homogeneous transformation matrix , this is a powerful tool for solving Forward kinematics ,In fig3 and Fig 4 we can observe the homogeneous transformation matrix which represents position and orientation of the end effector with respect to base frame in home position.

```
matrix =

[t1,    0,  0, d1]
[t2, pi/2,  0, d2]
[t3,    0, l1,  0]
[t4, pi/2,  0, d3]

>> DH_HTM(matrix, 'r')
Unrecognized function or variable 'DH_HTM'.

>> DH_HTM(matrix,'r')
Unrecognized function or variable 'DH_HTM'.

>> DH_HTM(matrix,'r')

ans =

[cos(t1 + t2)*cos(t3 + t4),      sin(t1 + t2), cos(t1 + t2)*sin(t3 + t4), d3*sin(t1 + t2) + l1*cos(t1 + t2)*cos(t3)]
[cos(t3 + t4)*sin(t1 + t2), -1.0*cos(t1 + t2), sin(t1 + t2)*sin(t3 + t4), l1*sin(t1 + t2)*cos(t3) - d3*cos(t1 + t2)]
[             sin(t3 + t4),                 0,         -1.0*cos(t3 + t4),                       d1 + d2 + l1*sin(t3)]
[                        0,                 0,                         0,                                        1.0]
```

Fig3 Homogenius Transformation matrix

```
ans =

[1.0,   0,   0,            0]
[  0, 1.0,   0,           d3]
[  0,   0, 1.0, d1 + d2 + l1]
[  0,   0,   0,          1.0]
```

Fig4 Position & orientation of the robot from Base to End Effector

The visualization of the robot is made using Robotics system Tool Box MATLAB[20] and DH parameters created in order to verify the robot DH parameters, as shown in fig 5 we could see all the links and distance between links, axes of rotation at each joints.

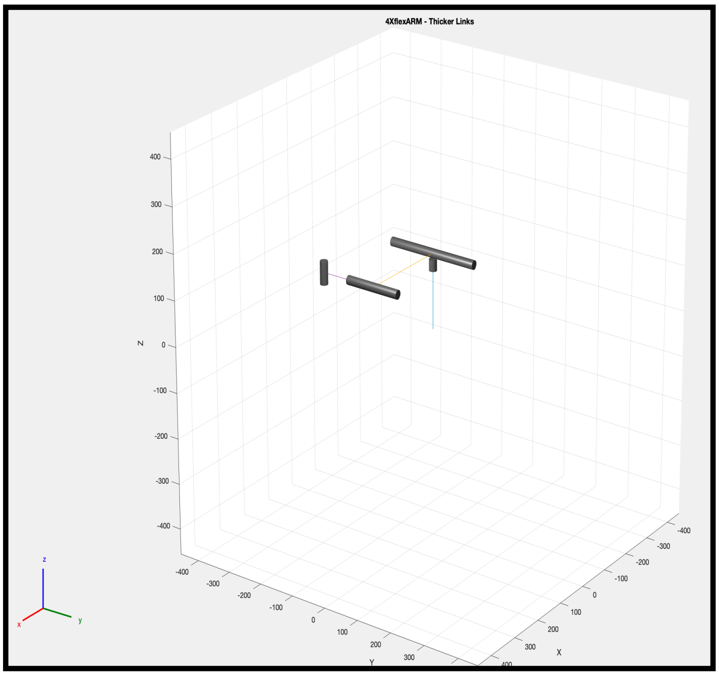

Fig5 Visualization of the robot using MATLAB RSTB

After solving Inverse kinematic using Analytical method the resolved θ1, θ2, θ3and θ4 are

$zreach = z - L1$

$reach = \sqrt{(r^2 + Z^2 reach)}$

$\theta 1 = arctan2(y, x)$

$cos(\theta 3) = (reach^2 - L2^2 - L3^2)/2(L2L3)$

$\theta 3 = arccos(clip(cos(\theta 3), -1,1))$

$k1 = L2 + L3cos(\theta 3)$

$k2 = L3sin(\theta 3)$

$\theta 2 = arctan2(Zreach, r) - arctan2(k2,k1)$

$\theta 4 = 0$

Set of all the Positions and orientations that the robot's end effector can reach comfortably(Reachable configuration of a robot) is know as Robots workspace[21] or a 3D volume of space that robots end effector can reach.The robots workspace is dependent on the length of the links and joints. Reachable Workspace is the volume of space the end-effector can reach in at least one orientation. Dexterous Workspace The Workspace that the end-effector can reach with all possible orientations it is smaller than the reachable Workspace. Our robots works calculate and graph using python's matplotlib library in fig6 we can observe the workspace of the robot.

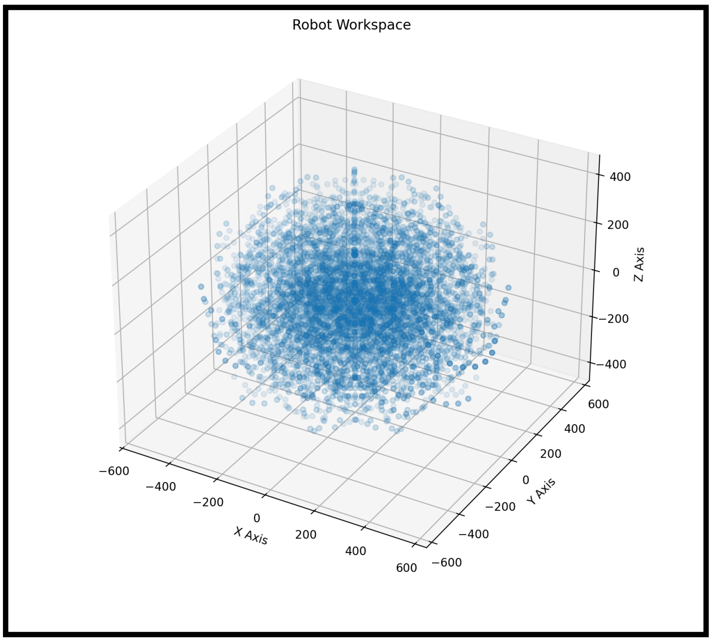

Fig6 Robots Work space

Whenever we work on any mechanical projects are being told before directly building the project first visualise the idea, this comes into life with the help of Softwares like FreeCAD, Solid Works etc.3D Modeling, simulation, motion analysis can be easily done by making use of these tools. In figure 7 we can observe the CAD design of the Robot, build using solid works.

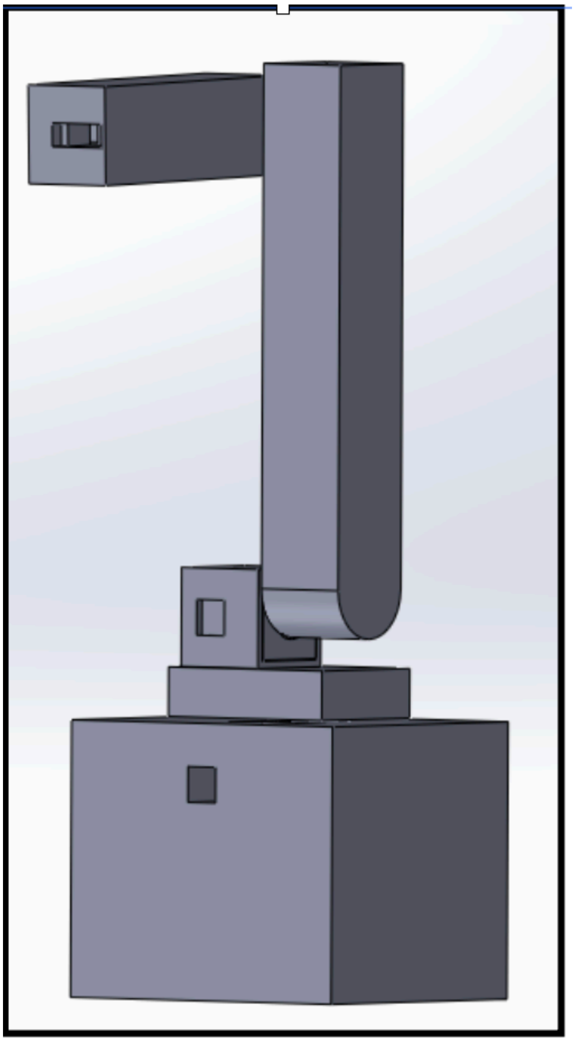

Fig7 CAD design

4. 1 Interface:

The novelty of our proposed approach combined high-torque NEMA17 motors with lightweight SG90 servos, achieving both power and precision in compact system. Additionally, the use of an 8051 microcontroller with a custom-built GUI in python provides a minimal cost, user-friendly interface for real-time control. The entire arm is 3D printed and designed for modular assembly, making it ideal for rapid prototyping and educational purposes.

InFig8 we have the Graphical user Interface of our project, with the help of UART cable we connect our PC to the 8051MicroController Board. We have 5 sliders for 5 motors ,When all motors are at 90 degrees that is the robots home position.when we move sliders right or left accordingly the angle will change in the robot, the GUI with serial communication sends commands to the 8051μC(like M1089 mentions the motor and 089 denotes the angle)Microcontroller is coded to receive the commands and perform action, when 8051μC receives a command it will look at the corresponding motor changes angle to step in case of stepper motors.In interface we have

Home button to set all the robot home configuration and Record Play buttons to perform specific task continuously (example : when Record Pick is used then after whatever changes made in sliders will saved in a array, when Play Pick is used all the angles stored in the array are passed as commands to the 8051μC) this is a simple interface that is used to communicate between user and Robot with the help of PC.

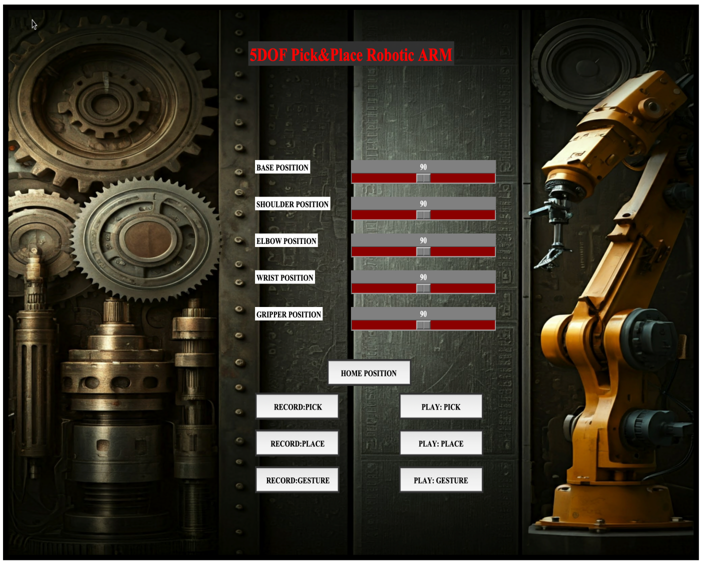

Fig8 GUI FlexArm5X

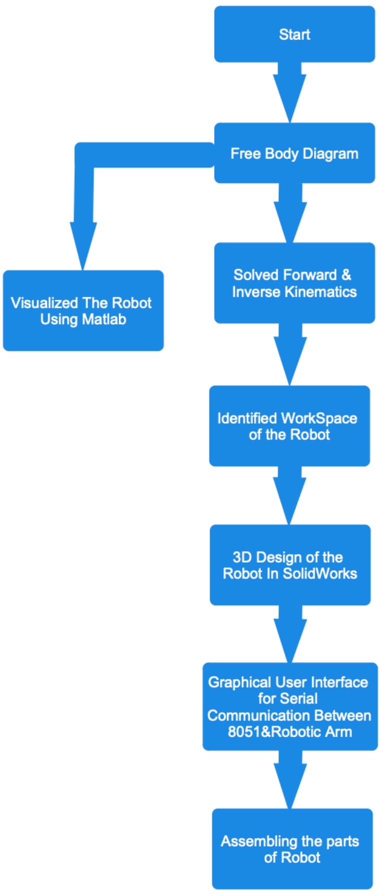

Fig9 Research Methodology

5. Results:

The developed 5-DOF Robotic Arm able perform the action that is coming from the interface to the 8051 microcontroller. Whenever angle is changed in the interface that is transferred to the microcontroller in the form of a command(like HOM ,M1090, M2180, etc..) then Motors Rotates accordingly.

Variations in Angles as shown in the fig10, microcontroller programming involves the reception of commands through serial communication using PL2303 USB to TTL connector, whenever the command is received the microcontroller will calculates the required Steps and Direction for stepper motors and Pulse Width for servos and move to required position. Fig11 shows the Robot position after performing the angle variations made in the FlexArm5X (GUI).

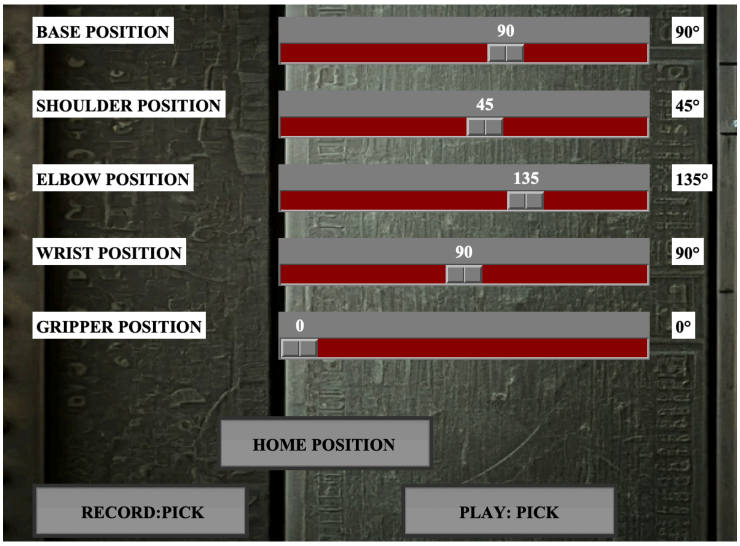

Fig10 Serial Communication through GUI

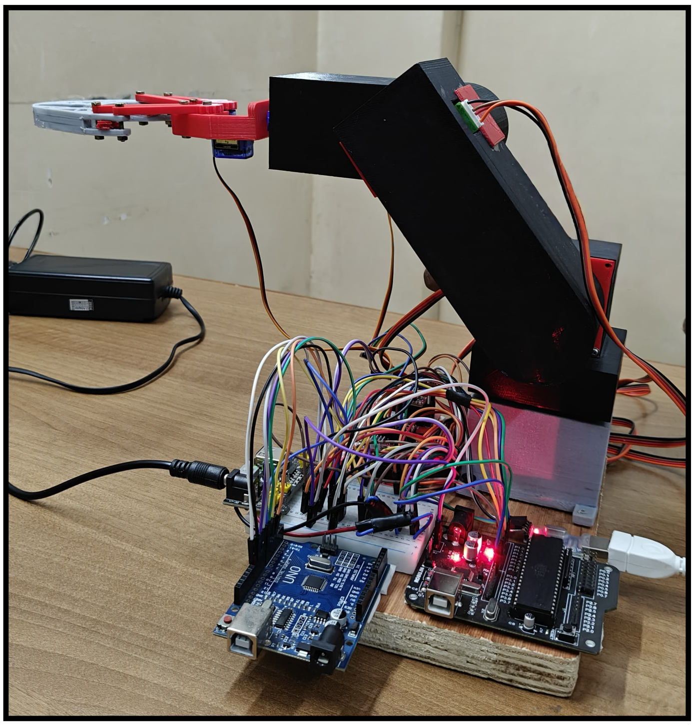

Fig11 Robots Position After Motion

6. Conclusion:

The implementation of the 5-DOF robotic arm for pick-and-place operations is working very precisely. Challenges such as cost efficiency, precision, and user-friendliness have been effectively addressed. By combining forward kinematics using Denavit-Hartenberg (DH) parameters with a custom graphical user interface, the system has demonstrated reliable performance in pick-and-place tasks. The use of 3D-printed components significantly contributes to affordability, while high-torque stepper motors ensure consistent and accurate movements. Through the integration of hardware and software, the robotic arm successfully full fills its intended purpose. This project highlights the potential of leveraging accessible fabrication techniques.

Our results show an accessible and low-cost Robotic Arm system without compromising on performance or precision, far cheaper than industrial robots. Furthermore, it serves as an ideal platform for students, researchers who wish to understand and explore the underlying technologies involved in robotic manipulation and control.

Future work: could focus on improving the arm's capabilities to make it even more user-friendly, Implementing Forward and Inverse Kinematics , trajectory Planning and Path Planning to make automations tasks .

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