DESIGN AND DEVELOPMENT OF 4 DOF ROBOTIC ARM

A Final Year Project Report

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by

Bushra Khalid
Hamdah Munir
Muhammad Rafay Faisal
Sannay Muhammad

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ABSTRACT

This project involves the design and development of a hybrid 4 DOF robotic arm for use in industrial automation applications. It is constructed using lightweight and high-performance materials and engineered with minimal moving mass, achieving outstanding performance while consuming a minimal amount of energy. The arm is designed to perform a range of tasks, including pick-and-place and material handling operations.

The design process began with the identification of parameters, followed by the development of mathematical model for the selection of motors. The arm was then modeled in CAD software to ensure it meets its intended specifications. Finite Element Analysis was carried out to assess the material and structural integrity of the design. The CAD model was used to machine the components of the robot. The control system and user interface were developed using microcontroller and GUI platform.

The arm was assembled, and the control system was tested to ensure that it could meet its intended specifications. The control was found to be capable of performing the tasks it was designed for, with precision and accuracy. The arm was controlled using a microcontroller, which allowed for precise movement and positioning.

The results of the project include a functional 4 DOF robotic arm that can be programmed to perform specific tasks. The arm has potential applications in industrial automation, where it could be used to increase efficiency and reduce labor costs. This project demonstrates the potential of robotics in industrial automation and provides a foundation for future research and development in this field.

In conclusion, this project has successfully designed and developed a 4 DOF robotic manipulator capable of performing a range of operations with precision and accuracy. The arm's potential applications in industrial automation make it an exciting development for the field. Future work could include further testing and development of the gripper, as well as exploring new applications for robotic automation.

ACKNOWLEDGMENTS

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CHAPTER 1: INTRODUCTION

Advancements in robotics have transformed the industrial sector by enabling cost-effective, efficient, and accurate automation of tasks.

1.1 Problem Statement:

The automation industry in Pakistan is currently limited to large MNCs due to the high cost of imported machinery and robots. This issue restricts the growth of small and medium-sized industries and increases their dependence on manual labor. Manual labor is less efficient, time-consuming, and costly as compared to robotics. Pakistan is ranked 105th out of 132 nations in the Global Innovation Index 2021 for invention, which is a major factor in automation (The World Bank 2021).

We aim to provide a cost-effective and efficient solution to the need for indigenous manufacturing of robots as an import replacement to the manufacturing sector of Pakistan.

1.2 Motivation of Work:

The motivation behind this project is to revolutionize the automated industry in Pakistan. The world is moving towards automation, and the use of robots has become increasingly common in various industries worldwide. Robotics technology has become the key driver of innovation in the manufacturing sector, with robots performing tasks that were previously impossible or too expensive for human workers to carry out. They are capable of performing repetitive and mundane tasks with great accuracy and speed, freeing up human workers to focus on more complex tasks.

However, the automated industry in Pakistan is still in its infancy, and the country relies heavily on imported machinery and robots. The cost of these imports is extremely high, making them unaffordable for most small and medium-sized businesses. The State Bank of Pakistan report claims that the majority of the nation's small and medium-sized firms (SMEs) make up the manufacturing sector and lack the capital and know-how to invest in automation. According to the paper, "SMEs have limited access to skilled labor, skilled technology, and financial resources—all of which are essential for modernizing their manufacturing processes." This situation limits the automated industry in Pakistan to only the largest multinational companies, leaving the vast majority of businesses with no option but to use manual labor for their operations. Only 20% of the 105 businesses questioned by the Pakistan Business Council said they had automated their production processes [1]. Large firms made up the majority of these businesses, whilst SMEs were less likely to automate.

The lack of affordable robotic technology has been a major barrier to the growth of the automated industry in Pakistan. This project aims to address this problem by developing a cost-effective, indigenous solution for the manufacturing of robots in the country. By doing so, we aim to support local industry by making it possible for businesses of all sizes to benefit from the advantages of automation. This will lead to increased efficiency, higher productivity, and ultimately, greater competitiveness for Pakistani businesses.

1.3 Objective of the Project:

The primary objective of the project is to design and manufacture a robotic arm that is cost-effective, energy-efficient, and has a wide reach, enabling smaller companies to improve their productivity. By doing so, the project aims to initiate the indigenous manufacturing of robots and introduce an import replacement for the local industry.

1.3.1 Deliverables

In addition to the primary objective, the project has several deliverables. These include:

- Development of mathematical Model of the robotic arm
  Design of kinematic model satisfying the acceleration and velocity objectives an kinetic model for the simulation of torques and selection of motors.

- Design and Simulation of CAD Model
  Design of structure of the robotic arm and FEA simulations to ensure structural integrity and selection of material.
- Fabrication of Robotic Arm
  Machining and assembling of parts through mechanical and chemical fasteners.
- Development of Control Systems and GUI
  Tunning of motors and motor drivers, programming the flow of commands using Arduino and developing a friendly-user interface to input instruction from the end user.
- Testing and Troubleshooting
  Testing the control system and robotic arm to ensure smooth operation and troubleshooting any issue that arises.

CHAPTER 2: LITERATURE REVIEW

2.1 Background

2.1.1 Evolution of Robotic Manipulators in Industry

Whilst the automotive industry currently dominates, the usage of manipulators is expanding in sectors like consumer products, food, manufacturing, and electronics. The goal of this project was to create a concept for a lightweight robot employing carbon fiber and aluminum lightweight materials. Also, the wrist must be built so that cables can pass through the inside. As changing cables is expensive, it is essential to design cables with less friction to extend the duration between maintenance. Based on the function analysis and the specified requirements' specifications, a concept generation was carried out. 24 sustainable concepts emerged that were divided into four groups [2].

2.1.2 Serial Manipulators

Simple repetitive tasks can be accomplished with optimum results by integrating autonomous robotic applications that keep the requirements of speed and accuracy in mind. Yet, it becomes a significant economic issue to be solved to develop these use for industries peculiar to nations like Nigeria, where there is readily available inexpensive labor. A direct control and drive mechanism was used in the creation of the serial manipulator mechanism by the authors. Using 3D printing technology, the arm's linkages are seen to be created using the CAD program Blender. The arm is moved by two servo motors, while the base is rotated by another servo motor [3]. Three knob switches and a toggle switch for the end effector are used to regulate the movements of the robot. A microcontroller is used to operate the motor. The electromagnetic end effector can be moved within a 40 cm hemisphere-shaped workspace. A payload of 15 N could be carried by the serial manipulator with ease. This article is a great example of a similar problem as in our country Pakistan. Third world countries can only afford to import machinery if they are Multi

National Companies. Hence, this project also uses this serial manipulator as an import replacement for their country that is cheaper and efficient.

2.1.3 Manipulators with Servo Motors controlled via LabView and Arduino

The robot is intended to carry out industrial tasks including the pick-and-place placement of hazardous chemical waste. Its robotic arm's unique characteristic is that it has a gripper system and can spin 360 degrees on its base. This robotic arm can rotate at the base and move forward and backward. A lab view software uses servo & DC motors, a computer, a motor drive IC and Arduino module to operate these functions and move the arm. As the end effector, a mechanical gripper has been created that can grab a variety of objects within the arm's workspace, even when there are outside disturbances. Two DC motors and four servo motors were successfully used to control the robotic arm assembly [4]. The robotic arm can accomplish a total of five degrees of freedom by regulating these six motors. The position control for the motors is implemented by Arduino. The experiment demonstrates how the Arduino can automatically modify its commands to match the arm motions and the task. While keeping simplicity of design, compactness, and lightness, the design strives to allow delicate manipulation for carrying out industrial operations.

2.2 Robotic Arms (Manipulators)

Following are the major types of robotic arms used in pick and place operations in the industry.

2.2.1 Cartesian Robots

These robots employ the Cartesian coordinate system, which involves linear movement along the three axes (X, Y, and Z) for forward and backward, up and down, and side to side motions. The three joints are translational and are limited to movement in a straight line, hence the name "linear" robots.

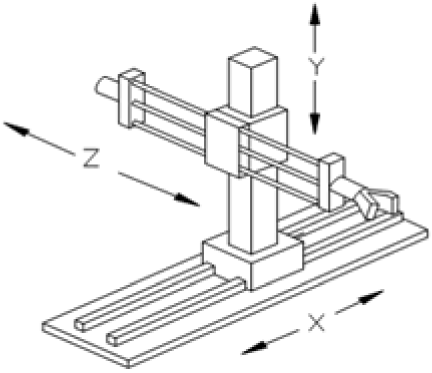


Figure 1 Cartesian Robot. [5]

Because they are inflexible in all three dimensions, linear robots are exceptionally precise and can produce repeatable results. They are also more straightforward than articulated robotic arms, with less complicated software control, and can be more cost-effective depending on the intended use.

However, they are comparatively slower than most of the SCARA and Delta robots. They require more space for mounting and operation. Lastly, due to incapable of rotational movements these robots cannot be used where reorientation of the end-factor is required.

2.2.2 SCARA Robots

A SCARA robot is a type of industrial robot with four axes of motion: two in the horizontal plane (X and Y) and two in the vertical plane (Z and rotation). The term SCARA stands for Selective Compliance Assembly Robot Arm or Selective Compliance Articulated Robot Arm, depending on the source.

Figure 2 SCARA Robot [5]

SCARA robots are often used in assembly and material handling applications, where they can perform tasks, such as pick-and-place operations, screwdriving, and fastening. Their arm design provides precision movement, making them ideal for applications that require repetitive motions. SCARA robots are also known for their ability to work in a confined space, which makes them well-suited for factory automation applications.

Owing to their design, they are faster than cartesian robots but slower than delta robots. They have a limited load carrying capacity.

2.2.3 Delta Robots

Delta robot is a type of parallel robot, generally features three or four lightweight arms made of carbon-fiber material that extend downward from the robot's main body. The arms are connected to the base through universal joints, which allows them to move in a spherical motion. The end effector is attached to the three arms, which enables it to move precisely and quickly within a three-dimensional workspace.

Figure 3 Delta Robots [7]

Delta robots are high speed and high precision robots, and they are mostly used in pick-and- place applications as well as packaging, and sorting. They are particularly well-suited for applications that require high-speed and repetitive movements. Owing to their complex design and complex movements, they require powerful programming compared to other robots.

Delta robots carry limited weights compared to their counter robots SCARA or cartesian. They also require a mounting structure making them unsuitable for application in limited space.

2.2.4 Hybrid Robots

Hybrid robots combine the best features of serial and parallel robots providing high speeds, high precision, long range, greater payload capacity capable of working in confined spaces.

Figure 4 Hybrid Robot [8]

Through its innovative design it provides lower moving masses and shorter cycle time reducing the power consumption and increasing efficiency.

2.3 Competitor

2.3.1 Cognibotics

Cognibotics is a Swedish company, that aims to contribute to the societal and industrial innovation through new robotics and automation solutions. It primarily focuses on utilization of hybrid kinematics of robot design to develop innovative solutions to the user's problem.

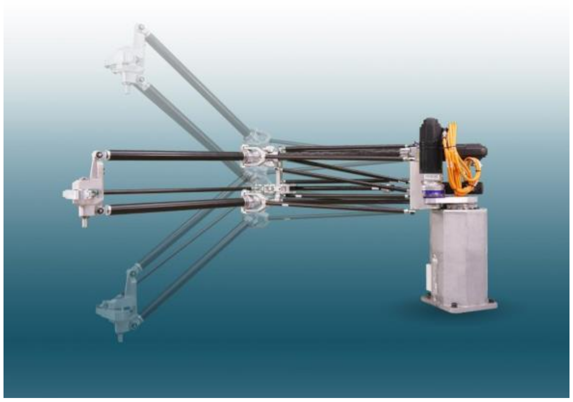


Figure 5: HMK 1800 Robotic Arm [8]

Their robot includes following features:

- 4 Axis motion: 3 Motors on the base, last motor at the gripper end.
- 2 kg nominal weight and 7kg maximum payload carrying capacity.
- 2.5g nominal acceleration and 8g maximum acceleration.

2.4 Mathematical Model

2.4.1 Kinematic Model

Kinematic model defines the motion of the robot without taking in account the cause of motion. It primarily covers the position, velocity, and acceleration of the end-effector with base.

Kinematic analysis is performed for the following reasons:

- Accurate positioning and orientation of end-effector: by establishing a relation between joint parameters and end-effector frame parameters.
- Kinematic model is used in calculation of kinetic model, utilized to find motor torque for motor selection.
- Kinematic equations are used in control systems.

Manipulators are made of nearly rigid links. Joints present at the intersection are used to connect these links. The joints are usually controlled and tuned with encoders and position sensors, which allow the relative motion of neighboring links to be monitored. For revolute joints, the motion occurs in terms of joint angles.

The number of degrees of freedom that a robot has is the number of independent motion and position variables that would have to be identified to position all links and end effect of the manipulator.

Factors that affect the Kinematic Model are:

- Link lengths
- Nature of Joints (rotary/prismatic)
- Joint Angle limits

Following are the two types of kinematic model evaluated to completely study the motion of a manipulator:

- Forward Kinematics
- Inverse Kinematics

2.4.1.1 Forward Kinematics:

Forward kinematics is a technique used in robotics to determine the position and orientation of the end effector (the tool or device attached to the robot's arm) based on the position and orientation of the robot's joints. [7]

In forward kinematics, the transformation matrix is used to calculate the end effector's position coordinates and orientation in cartesian space, when the joint angles are given. This transformation matrix is defined by the robot's kinematic model, which describes the relationship between the robot's joints and the end effector.

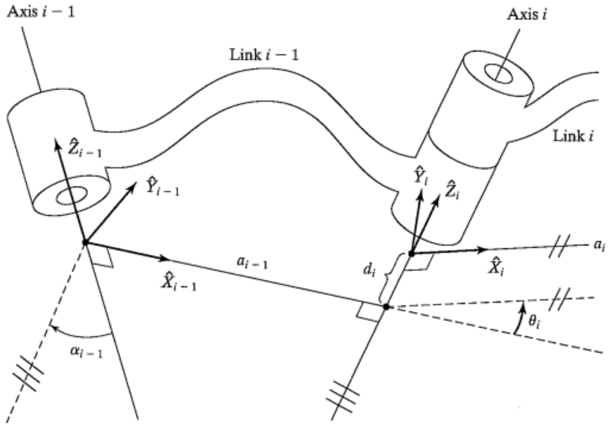


Figure 6 Linkages and Joints [7]

2.4.1.2 Joint Angles to End-Effector Position and Orientation:

$$X = {}^{0}_{4}T$$

Transformation Matrices

The first objective of the kinematic model is to translate the joint angles to the gripper plane position and orientation. This is done using transformation matrices, which can be formed using basic principles of frame translation and rotation about a certain axis. It is a 4x4 matrix consisting of 3x3 rotation matrix and 3x1 position matrix relating frame of previous joint to the frame of next joint.

2.4.1.3 Denavit–Hartenberg Parameters

2 link definition parameters and 2 motion definition parameters also known as Denavit-Hartenberg (DH) parameters are used to describe the kinematics of manipulators with rotary joints. The DH parameters describe the relationship between each pair of adjacent links in the robot's arm. By defining these parameters for each link in the robot's arm, it is possible to create a kinematic model that can be used to calculate the gripper’s position and orientation for a given set of joint angles.

Following are the rules to calculate DH parameters [7]:

$$a_i = the\ distance\ from\ \hat{Z}_i\ to\ \hat{Z}_{i+1}\ measued\ along\ \hat{X}_i$$

$$\alpha_i = the\ angle\ from\ \hat{Z}_i\ to\ \hat{Z}_{i+1}\ measued\ about\ \hat{X}_i$$

$$d_i = the\ distance\ from\ \hat{X}_{i-1}\ to\ \hat{X}_i\ measued\ along\ \hat{Z}_i$$

$$\theta_i = the\ angle\ from\ \hat{X}_{i-1}\ to\ \hat{X}_i\ measued\ about\ \hat{Z}_i$$

2.4.1.4 Joint Velocities to End-Effector Velocity:

Joint velocity can be related to the end-effector velocities using Jacobian matrix which can be obtained by derivation of transformation matrix elements. The Jacobian matrix consists of 3 positional velocity elements and 3 rotational velocity elements.

$$V = J \times \dot{\theta}$$

Joint Accelerations to End-effector Acceleration:

The relation between joint acceleration to end-effector acceleration is obtained using the velocity equation. It consists of 3 translational and 3 rotational components.

$$A = \dot{J}\dot{\theta} + J\ddot{\theta}$$

2.4.1.5 Inverse Kinematics

Inverse kinematics (IK) is used to determine the required joint angles or parameters needed to achieve a desired end effector position or pose.

- Inverse kinematic model is studied to identify the singularity points of a robot.
- It is used in control system development, back-solving the end-effector position that is desired to the joint-angles that are required to achieve it.

Singularities are the points where robot loses it one of more than one degree-of-freedom. At singularity the inverse-kinematic model yields infinite end-effector velocity and acceleration. These points are removed and avoided from the workspace to achieve better performance. The determinant of Jacobian matrix is zero at the point of singularity.

$$|J| = 0$$

2.4.2 Kinetic Model

The kinetics of a robotic arm refers to the study of the motion, forces, and torques involved in the movement of the arm. This includes the dynamics of the arm, which is the study of the forces and torques that cause the arm to move and change its velocity and direction.

The kinetics of a robotic arm can be described using mathematical models that take into account the arm's structure, the physical properties of its components, and the torques and forces acting on it.

We required kinematic model to:

1. Select joint motors
2. predict the arm's motion
3. design controllers that can regulate its movement

There are several factors that affect the kinetics of a robotic arm, including the size and weight of the arm, the type of motors and actuators used to control its movement, and the environment in which it operates. For example, a heavier arm will require more force to move and will be more difficult to control, while an arm operating in a crowded or cluttered environment may require more precise movements to avoid obstacles.

The two most widely used formulations to derive equation of motion of robotic manipulator are:

1. Newton-Euler formulation
2. Euler-Lagrange formulation

Both formulations give same equation of motion.

2.4.2.1 Newton-Euler formulation

It uses force balance to derive equation of motion of manipulator. Newton-Euler formulation is based on:

1. Newton's laws of motion, which state that the net force acting on a body is equal to the mass it possesses multiplied by its acceleration:

$$F = ma$$

2. Euler’s equation, which states that the net torque applied on a body are equal to its moment of inertia multiplied by its angular acceleration.

$$\tau = I\alpha$$

This formulation is well-suited for analyzing the dynamics of systems that involve multiple rigid bodies, such as robotic arms, and is often used to derive equations of motion and to develop control algorithms for robotic systems.

$$\therefore \boldsymbol{\tau} = \mathbf{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{v}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta})$$

where M is then x n mass matrix of the manipulator, V is an n x 1 vector of centrifugal and Coriolis terms and is an n x 1 vector of gravity terms. [7]

Strengths:

- It is well-suited for analyzing the dynamics of multi-body systems, such as robotic arms.
- It can be used to solve the equations of motion for robotic systems with both translational and rotational degrees of freedom.
- It is often used in control and trajectory planning algorithms for robotic systems.

Weaknesses:

- It can be computationally intensive, especially for complex systems with many degrees of freedom.
- It does not take into account the effects of flexible components in the system.
- It may not be suitable for systems that exhibit large deformations.

2.4.2.2 Euler-Lagrange formulation

It uses energy balance to derive equation of motion of manipulator. Euler-Lagrange formulation, on the other hand, is based on the principle of least action, which states that a system will follow the path of least action between two points in time. This formulation is often used to derive the equations of motion for systems with flexible components, such as robotic arms with flexible joints or links. The Euler-Lagrange formulation takes into account

1. the kinetic energies of the mechanism

$$K = \sum_{i=1}^{n} k$$

2. the potential energies of the mechanism

$$U = \sum_{i=1}^{n} u$$

It is useful for analyzing the behavior of the system over time.

$$\therefore \frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q_i}}\right) - \frac{\partial \mathcal{L}}{\partial \dot{q}} = \tau_i$$

where $\mathcal{L}$ is Lagrangian, the difference between the kinetic and potential energy. [7]

Strengths:

- It takes into account the effects of flexible components in the system, making it suitable for systems with large deformations or with significant flexibility.
- It is useful for analyzing the behavior of the system over time.
- It is used to solve the motion equations for a wide variety of mechanical systems, including those with non-holonomic constraints.

Weaknesses:

- It can be more difficult to apply to systems with many degrees of freedom, especially if the system has non-linear dynamics.
- It may require more sophisticated numerical methods to solve the equations of motion.
- It may not be well-suited for systems that involve contact or impact dynamics.

2.5 Control System

2.5.1 PLC and Microcontroller

2.5.1.1 PLC

PLC acronym for Programmable Logic Controller is a digital computer used in industrial applications, particularly in automation and control systems. It is designed to control and automate a wide range of processes, such as manufacturing processes, assembly lines, and material handling systems. They are robust, reliable, and designed to work in harsh environments.

Figure 7 PLC [8]

PLC are more suited in heavy industrial applications; they require more complex programming and are expensive than most microcontrollers for small scale applications.

2.5.1.2 Arduino

Arduino is an open-source electronics platform used in industrial as well as hobbyist projects. It is based on easy-to-use software, having its own coding application along with flexible hardware which allows multiple devices to integrate. It consists of a microcontroller board with various input and output pins and a development platform where users can write and upload code to the Arduino board.

Figure 8 Arduino Uno Microcontroller [9]

These are more reliable, cheap, and suitable for small scale applications in industrial automation. They offer flexible mounting and are more portable than other controllers.

They have following features:

- Timer Interrupts: This feature allows parallel monitoring of the output and input of devices using a 16MHz crystal oscillator and executes IRS, reducing the delays.
- It can generate pulses with a time-period of minimum 62.5ns. It has multiple 16- and 8-bit counters, that can count to 65,536 oscillations.
- Arduino Mega has 56 digital pins, 16 Analogue pins, and support UARTs, SPI and I2C communication protocols.
- Usually, an Arduino board costs around 3,000 to 6,000 PKR.

2.5.2 Graphic User Interface:

A user interface that uses graphical elements i.e., icons, menus, windows, and buttons, which allow users to communicate with an application visually is called a Graphical User Interface. A GUI enables users to control a robotic arm by providing an intuitive interface that allows users to interact with the robotic arm using graphical elements such as buttons and sliders.

A robotic arm is a complex system that requires precise control, and a GUI can make it much easier to operate. With a GUI, users can quickly and easily set the position, orientation, and speed of the robotic arm. This is especially important when dealing with more advanced robotic arms that have multiple degrees of freedom, since these can be difficult to control without an intuitive interface.

In addition to making it easier to control the robotic arm, a GUI can also provide feedback to the user on the current state of the robotic arm. This can include information such as the position, speed, and status of the arm, as well as any error messages that may occur during operation.

We required GUI to [10]:

1. Take position, orientation, and speed input from user
2. Use them to calculate joint angles and velocities using inverse kinematics
3. Convert them to number of pulses and frequency for each joint motor
4. Communicate it to microcontroller to generate required pulses and frequency

CHAPTER 3: METHODOLOGY

The methodology is primarily divided into 3 parts, addressing different areas of projects:

- Mathematical Approach
- Design Approach
- Control Systems

3.1 Mathematical Approach

3.1.1 Kinematics: Position, Velocity and Acceleration Equations and Calculations

3.1.1.1 Position and Pose

DH principles were used to construct a table consisting of 4 DH parameters that related one joint frame to its adjacent joint frame.

- This method was adopted instead of direct transformation matrix formation as it provides a systematic and consistent way of describing the geometry of a robotic arm with rotary joints, making it easier to design, model, and control the arm.

The DH parameters were then converted to transformation matrix using standard rules.

The relation between the joint angles and end-effector position and pose is obtained by multiplying all the transformation matrices of each link.

$$
{}^{i-1}_{\quad i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

3.1.1.2 Velocity

The elements of transformation matrices are then differentiated to form a Jacobian of the robotic model. That relates the joint velocities to the end-effector velocities of the robotic arm.

$$J_v = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial \theta_3} & \frac{\partial x}{\partial \theta_4} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial \theta_3} & \frac{\partial y}{\partial \theta_4} \\ \frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \frac{\partial z}{\partial \theta_3} & \frac{\partial z}{\partial \theta_4} \end{bmatrix}$$

3.1.1.3 Acceleration

Differentiating the velocity equation with respect to time results in the acceleration equation of robot kinematic model that is used to relate the joint accelerations with end-effector acceleration.

Singularities

The singularities were checked by putting the determinant of the Jacobian matrix to zero and solving for the equation.

3.1.2 Kinetics: Torque Equations and Calculations:

Out of two formulations for equation of motion derivation and torque calculation, we opted for Euler langrange formulation instead of newton Euler formulation. This is because Newton Euler formulation can be computationally intensive, especially for complex systems with many degrees of freedom and Euler langrange formulation is useful for analyzing the behavior of the system over time, which is our case.

We use values of velocity and acceleration computed from kinematic analysis in kinetic analysis. We derive inertia tensor matrices for each link and compute kinetic energies. We compute potential energies and then find langrange which is difference of kinetic and potential energies. Putting the values of langrange for each link and taking partial derivatives as required by equation, we find equation of motion of robotic arm as well as joint torques required at each joint.

These torques are the theoretically calculated values which must be provided by motors after the losses in order to achieve desired velocities and accelerations and to carry its own mass and payload.

3.2 Design Approach

The literature review was followed by the fabrication of the robotic arm. The arm is designed to have a maximum reach of 1800mm. The nominal payload it is designed for is 2kg. The arm has 4 DOF that it can rotate around. This fabrication was done keeping in mind the required results from this robotic arm i.e., low weight, high speed and acceleration used for pick and place industry. The design of the robotic arm was done on Solidworks software. Ansys was used to run simulations and test it.

The design and fabrication consisted of the following concept:

1. Design of the robotic Arm
2. Market Visit
3. Material Selection
4. Procurement of Material
5. Machining of Part
6. Assembly

CAD Designs of the parts are present in APPENDIX II

3.2.1 Joint 1

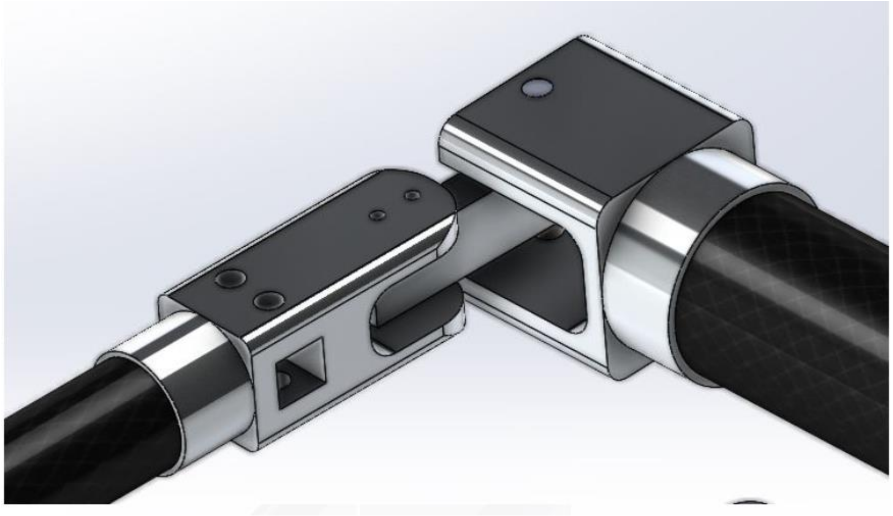


Figure 9 Joint 1

3.2.1.1 Part 1

The first part of joint 1 is shown in figure 1. This part was designed in Solidworks. The part acts as the holder of first link (carbon fiber tube) and joins is to the second links parts through a pin joint. The material selected for its fabrication was aluminum because of its low weight and durability. The part was machined using CNC machine.

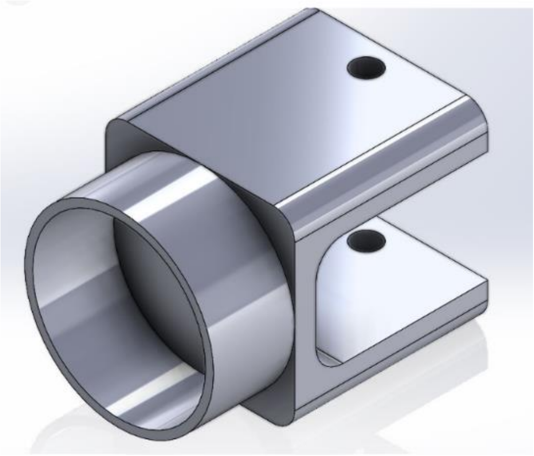


Figure 10 Part1 of First Joint

3.2.1.2 Link 1

The first link is attached between the second motor and the first joint. It is a carbon fiber tube as shown in figure 2 because of its low weight and high strength. The inner diameter of the tube is 60mm with a thickness of 2mm.

Figure 11 Carbon fiber tube acting as Link 1

3.2.1.3 Part 2

This part as shown in figure 3 acts as a spacer to increase the length between the two parts of joint 1. This helps the joint to move in a range of 0 to 90 degrees. This was machined using Milling Manual Machine using an Aluminum part.

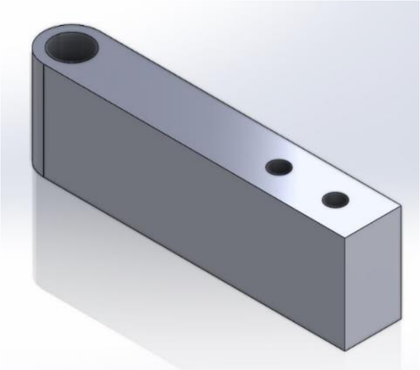


Figure 12 Figure shows spacing part of joint 1

3.2.1.4 Part 3

Part 3 is the holder of link 2 (carbon fiber tube) and joints it to the part 1 using spacer in between as shown in figure 4. They are pin connected. The material used is again

Aluminum and it is also machined on CNC. The part has a rectangular slot in it for another part.

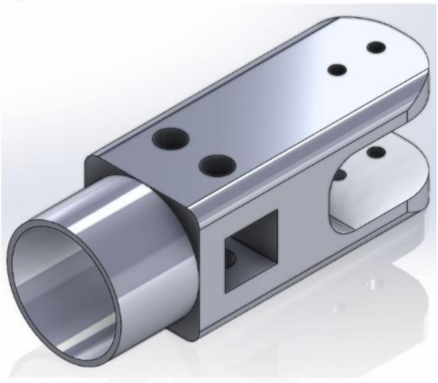


Figure 13 Figure shows part 3 of joint 1

3.2.1.5 Link 2

Link 2 is another carbon fiber tube of inner diameter of 36mm with a thickness of 2mm.

This is shown in figure 5.

Figure 14 Carbon Fiber rod Link 2

3.2.2 Joint 2

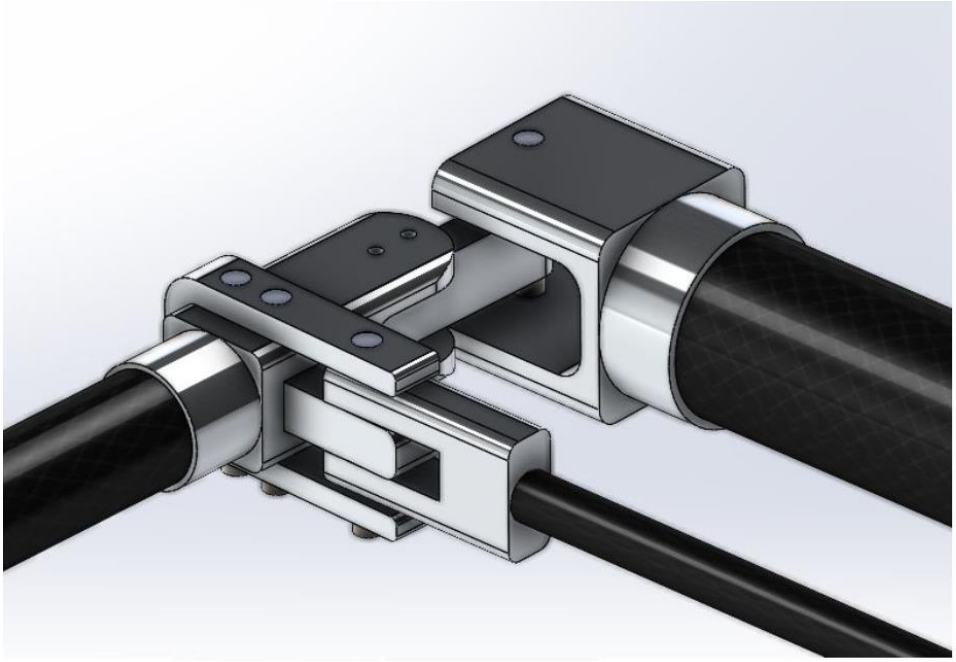


Figure 15 Figure shows Joint 2 assembly

3.2.2.1 Part 1

This part is made of Aluminum and fits in the rectangular slot of joint 1 part 3. It connects link 3 to joint 1. The part was manufactured using CNC machine.

Figure 16 Figure shows part 1 of joint 2

3.2.2.2 Part 2

Part 2 acts as the holder of link 3 (carbon fiber tube) and connects link 3 with the joint 1. It ensures 30 degrees rotation of the second axis.

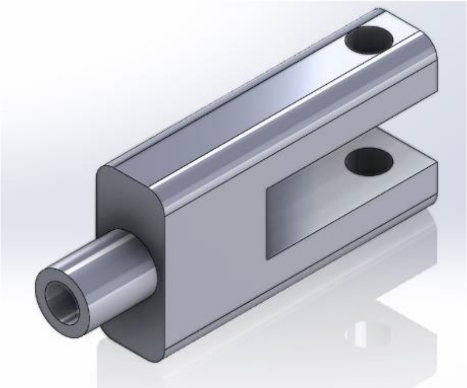


Figure 17 Figure shows part 2 of joint 2

3.2.2.3 Link 3:

Link 3 is attached to the motor and moves the joint 2. The link is a carbon fiber rod of diameter 16mm and thickness 1mm.

Figure 18 Figure shows link 3 made of carbon fiber

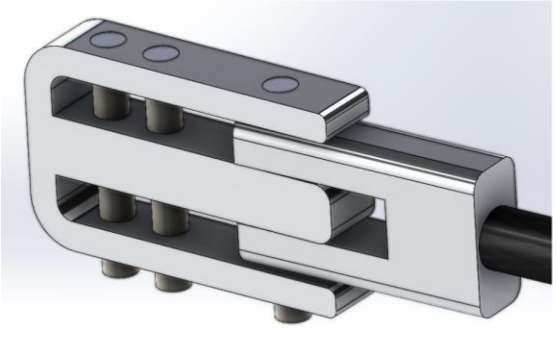


Figure 19 Figure shows assembled part s of joint 2

3.2.3 Fourth Axis Linkage

3.2.3.1 Component 1

This component works to provide 360 degree tool rotation at the end effector. A crank rocker mechanism is designed whereby translatory rocker motion is converted into rotary motion at the end effector.

Figure 20 Fourth axis linkage

3.2.4 Other Components

3.2.5 Motor Couplings

Low weight silver jaw couplings are used to join motor shafts with linkages. They are additionally used with Teflon bushings for better fittings.

Figure 21 Jaw coupling

3.2.6 Rod Ends

8mm rod ends are used with supporting linkages to allow for all degree slight movement of linkages.

Figure 22 Rod Ends

3.2.7 Ball Bearing

A deep groove ball bearing SKF 6014 is used over the first linkage.

Figure 23 Ball Bearing

3.3 Control System

Code for Arduino is written in APPENDIX III

3.3.1 Arduino Microcontroller

Arduino Mega 2560 consisting of AtMega2560 chipset was used as it consists of following features:

- 54 digital and 16 analogue pins, which are far greater than its other models.
- Four 16-bit counters, compared to only one 16-bit counter in its other model.
- More interrupts, pre-scaler, and count limits suitable for robotic applications.

Arduino microcontroller was chosen as it provides following advantages over the PLC:

- Cost: PLCs are generally more expensive than Arduinos, especially for small-scale applications. PLCs are designed for industrial-grade applications, which typically require more robust hardware and software, resulting in higher costs.
- Programming complexity: The programming languages used for PLCs, such as ladder logic, can be more complex than Arduino's C/C++ programming language. This can make programming more complex and time-consuming.
- Limited community support: While PLCs have been used in industry for many years, the community support, and resources available are not as extensive as those for Arduinos. There is a wealth of information and resources available for Arduino users online, which makes it easier to troubleshoot and find solutions to problems.
- Limited flexibility: PLCs are designed for specific industrial applications and may not be as flexible as Arduinos when it comes to customizing the hardware and software for specific applications.
- Portable: Arduino are more portable, offer flexible mounting and requires less space compared to PLC.

Arduino microcontroller was used to take input from the LabVIEW GUI using SPI communication protocol. This protocol was opted due to:

- Faster data transfer rate.
- Duplex Communications: Data can be transferred and received at the same time.
- More Reliable: uses synchronous clock signals for communication.
- Longer Distance communication.

Once the input was received, it was programmed to calculate the pulses and frequency required to produce the desired output motion.

The timer interrupt and IRS function were utilized to generate pulses of different frequencies. The interrupt feature monitored the pulses in parallel, reducing the delay in pulse generation and ensuring high frequency waves resulting in higher velocities.

3.3.2 Graphic User Interface: LabView

According to the requirements of GUI listed in literature review for our robotic arm, the easiest to use, simple and widely used solution was LabVIEW.

LabVIEW acronym for Laboratory Virtual Instrument Engineering Workbench is a engineering system software platform designed for instrument control, data acquisition, and industrial automation. It is widely used in engineering and research laboratories, manufacturing plants, and educational institutions worldwide.

LabVIEW provides a graphical programming environment that allows users to create virtual instruments (VIs) by assembling blocks of code, called "nodes," that represent different functions, such as data acquisition, signal processing, and user interface design. These VIs can be used to interact with a variety of hardware devices, including sensors, motors, and other electronic components, as well as to interface with other software systems.

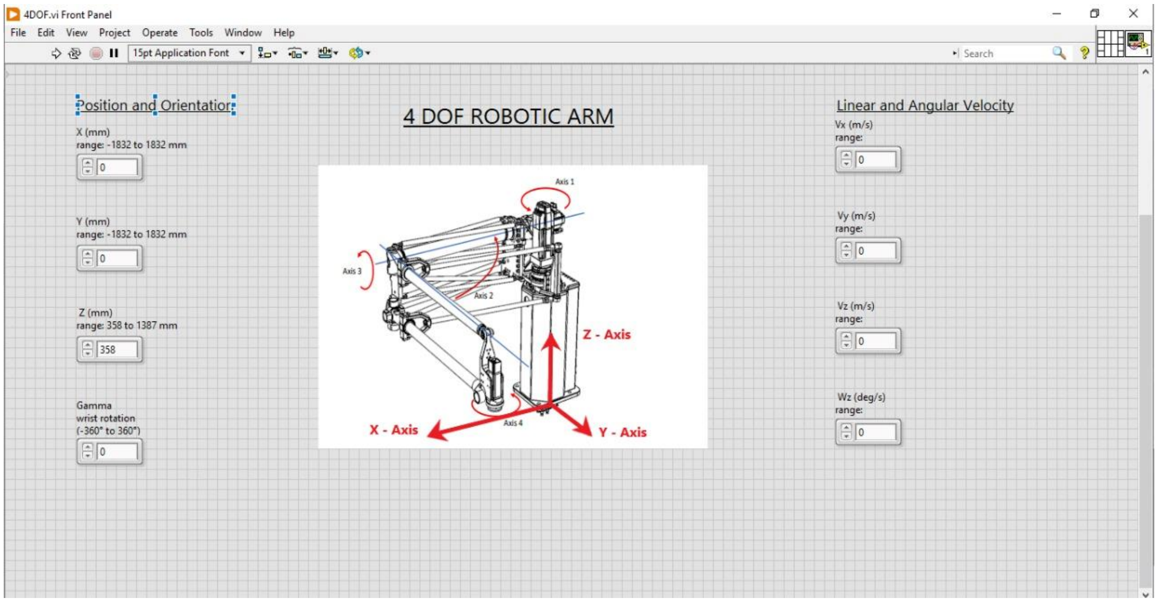
Labview has a front end and a block diagram.

3.3.2.1 Front-End:

The front-end of LabVIEW is the graphical user interface (GUI) of the program. It includes the panel, which is the part of the interface where users can interact with the VI by controlling its inputs and observing its outputs. The front-end also includes the toolbar, menus, and other interface elements that allow users to control the behavior of the VI.

We developed front end which takes from user input of

1. position in X, Y and Z
2. orientation
3. velocity in X, Y and Z



Position and Orientation

X (mm)
range: -1832 to 1832 mm
0

Y (mm)
range: -1832 to 1832 mm
0

Z (mm)
range: 358 to 1387 mm
358

Gamma
wrist rotation
(-360° to 360°)
0

Linear and Angular Velocity

Vx (m/s)
range:
0

Vy (m/s)
range:
0

Vz (m/s)
range:
0

Wz (deg/s)
range:
0

Figure 24 Front-End GUI LabVIEW

3.3.2.2 Block Diagram:

The block diagram is the core of LabVIEW's graphical programming environment. It is where users create and edit the code of the VI by connecting various nodes to represent different functions and operations. Nodes are graphical representations of code elements, such as mathematical operations, data manipulation functions, and control structures, which can be dragged and dropped onto the block diagram to build the VI's logic.

We developed block diagram that:

- confirms velocity and position are within reachable ranges.
- use MATLAB script to find joint angles, velocities and directions using inverse kinematics equations.
- converts joint angle to 16 bits.
- communicate it to microcontroller using SPI read.

The block diagram and front panel are connected through input and output terminals, which allow users to control the VI's behavior from the front panel and observe its results in real-time. When a user runs a VI, LabVIEW compiles the graphical code into executable machine code, which can be executed on the target hardware in real-time. This graphical approach to programming makes it easy to create and modify VIs, even for users with little or no programming experience.

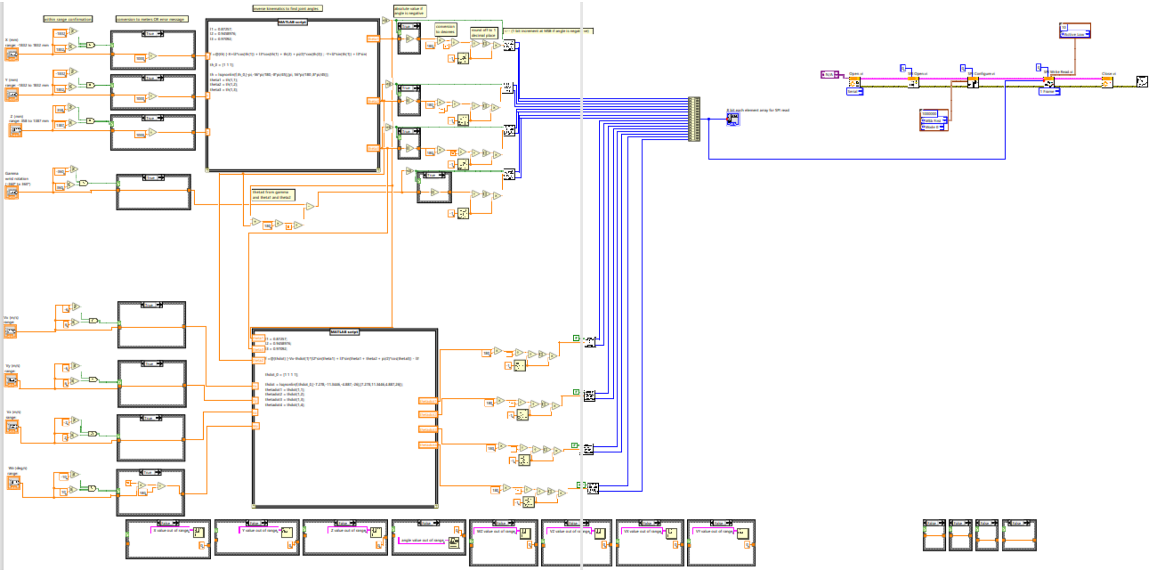


Figure 25 Block-Diagram LabVIEW

CHAPTER 4: RESULTS AND DISCUSSIONS

The analysis has been divided into 3 parts:

- Mathematical Model
- CAD Design and FEA Simulation
- Control System Design

4.1 Mathematical Model

MATLAB code written and executed for the calculation and design of mathematical is present in APPENDIX I.

4.1.1 Kinematics

The kinematic model is essential for accurate position control, motion control and pose orientation of the end-effector.

4.1.1.1 DH Parameters

Utilizing the methodology mentioned above, following DH parameters were calculated:

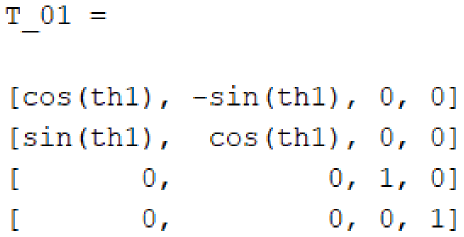
Table 1: DH Table

$\boldsymbol{i}$	$\boldsymbol{\alpha_{i-1}}$	$\boldsymbol{a_{i-1}}$	$\boldsymbol{d_i}$	$\boldsymbol{\theta_i}$
1	0	0	l_1	θ_1
2	0	l_2	0	$\widehat{\theta_2} = \theta_2 + \pi/2$
3	$\pi/2$	0	0	θ_3
4	$-\pi/2$	l_3	0	θ_4

Utilizing the formula [7]:

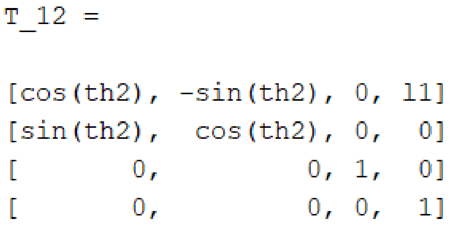
$$
{}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

The transformation matrices ${}^{0}_{1}T, {}^{1}_{2}T, {}^{2}_{3}T, {}^{3}_{4}T$ were obtained:



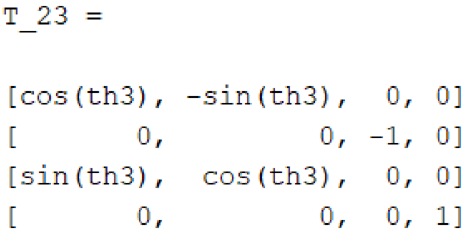
```
T_01 =

[cos(th1), -sin(th1), 0, 0]
[sin(th1),  cos(th1), 0, 0]
[       0,         0, 1, 0]
[       0,         0, 0, 1]
```



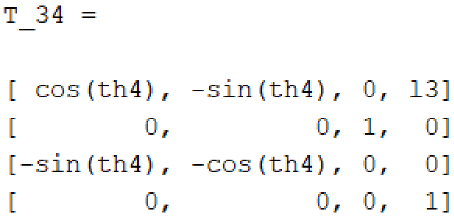
```
T_12 =

[cos(th2), -sin(th2), 0, l1]
[sin(th2),  cos(th2), 0,  0]
[       0,         0, 1,  0]
[       0,         0, 0,  1]
```



```
T_23 =

[cos(th3), -sin(th3),  0, 0]
[       0,         0, -1, 0]
[sin(th3),  cos(th3),  0, 0]
[       0,         0,  0, 1]
```

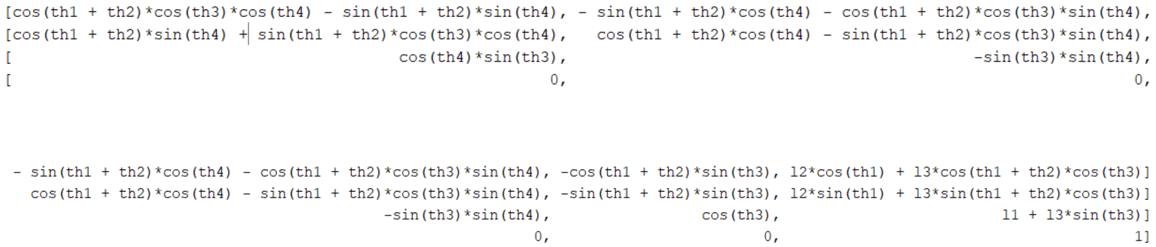


```
T_34 =

[ cos(th4), -sin(th4), 0, l3]
[        0,         0, 1,  0]
[-sin(th4), -cos(th4), 0,  0]
[        0,         0, 0,  1]
```

All of these were multiplied to get final transformation matrix, which related joint angles to end-effector position and pose:

$$
{}^{0}_{4}T = {}^{0}_{1}T \times {}^{1}_{2}T \times {}^{2}_{3}T \times {}^{3}_{4}T
$$



```
[cos(th1 + th2)*cos(th3)*cos(th4) - sin(th1 + th2)*sin(th4), - sin(th1 + th2)*cos(th4) - cos(th1 + th2)*cos(th3)*sin(th4),
[cos(th1 + th2)*sin(th4) + sin(th1 + th2)*cos(th3)*cos(th4),   cos(th1 + th2)*cos(th4) - sin(th1 + th2)*cos(th3)*sin(th4),
[                                         cos(th4)*sin(th3),                                             -sin(th3)*sin(th4),
[                                                         0,                                                              0,
```

```
 - sin(th1 + th2)*cos(th4) - cos(th1 + th2)*cos(th3)*sin(th4), -cos(th1 + th2)*sin(th3), l2*cos(th1) + l3*cos(th1 + th2)*cos(th3)]
   cos(th1 + th2)*cos(th4) - sin(th1 + th2)*cos(th3)*sin(th4), -sin(th1 + th2)*sin(th3), l2*sin(th1) + l3*sin(th1 + th2)*cos(th3)]
                                           -sin(th3)*sin(th4),                 cos(th3),                      l1 + l3*sin(th3)]
                                                            0,                        0,                                     1]
```

Figure: Final transformation matrix column 1 & 2 (above), column 3 & 4 (below)

4.1.1.2 Jacobian Matrix:

Jacobian matrix was obtained by differentiating the x, y and z elements of the of the position vector present in the final transformation matrix with joint angels.

The Jacobian obtained was a 6x4 non-square matrix.

$$J = \begin{bmatrix} -l_2 s_1 - l_3 s_{12} c_3 & -l_3 s_{12} c_3 & -l_3 c_{12} s_3 & 0 \\ l_2 c_1 + l_3 c_{12} c_3 & l_3 c_{12} c_3 & -l_3 s_{12} s_3 & 0 \\ 0 & 0 & l_3 c_3 & 0 \\ 0 & 0 & s_{12} & -c_{12} s_3 \\ 0 & 0 & -c_{12} & -s_{12} s_3 \\ 1 & 1 & 0 & c_3 \end{bmatrix}$$

The Jacobian is utilized in calculations of Singularities and Velocity equation.

4.1.1.3 Singularities:

To find the singularities of our model, the Jacobian had to be first converted into a square matrix, for that we multiplied its transpose with itself and then its determinant was equated to zero.

After applying the real-number conditions and angle ranges on the equation, the code (APPENDIX I) was executed.

Which resulted in no solution being found. Therefore, considering our workspace and angle ranges, no singularity was identified.

4.1.1.4 Velocity Equations:

The velocity of the end-effector was related to the joint velocity using following equation:

$$V = J \times \dot{\theta}$$

The end effector velocity range was calculated over the workspace, by implementing the equations over a grid of workplace points (different initial conditions) and using maximum joint angle velocities. Following plots and results were obtained to note maximum values:

Velocity component (x-axis):

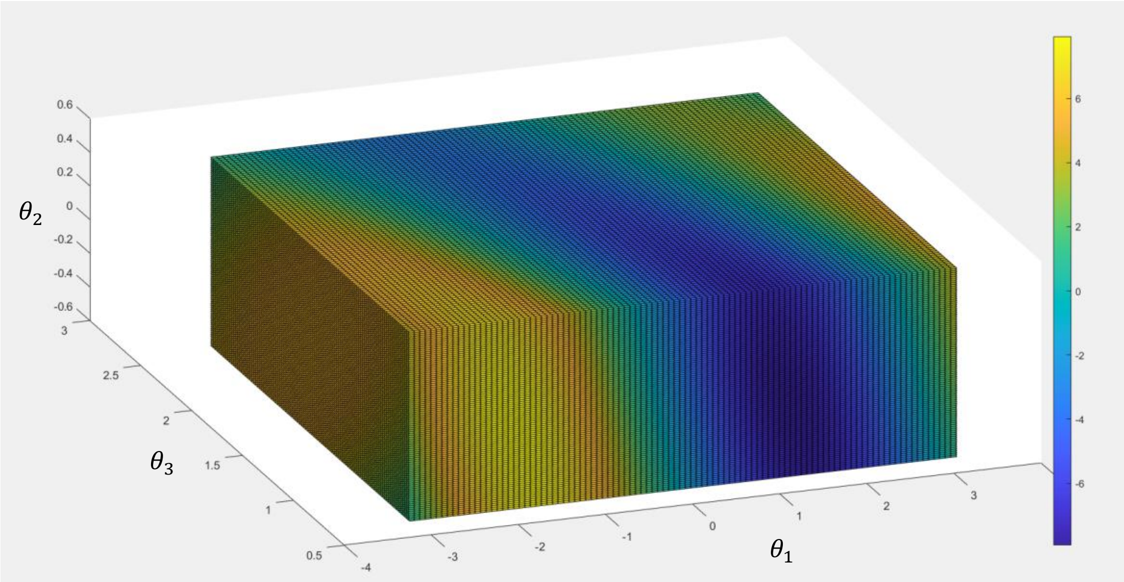


Figure 26 Plot of V_x end-effector velocity, x-component across workspace.

elocity component (y-axis):

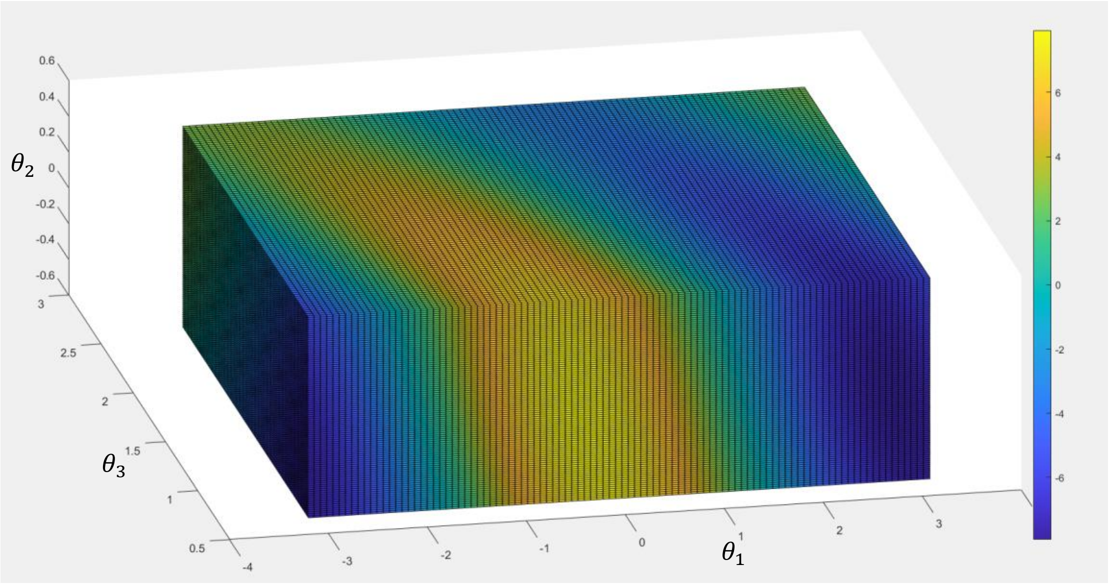


Figure 27 Plot V_y end-effector velocity, y-component across workspace.

Velocity component (z-axis):

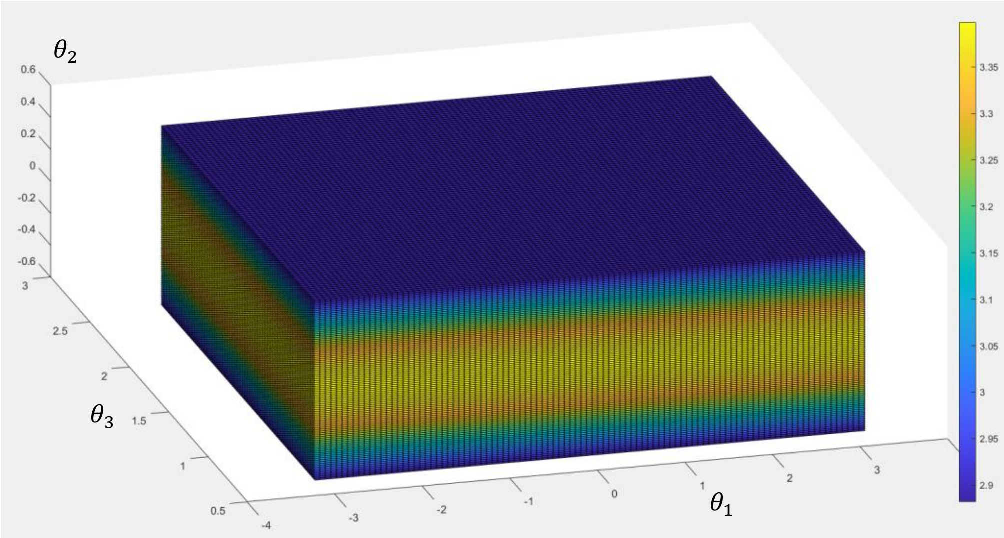


Figure 28 Plot V_z end-effector velocity, z-component across workspace.

Pose/Orientational Velocity component (z-axis):

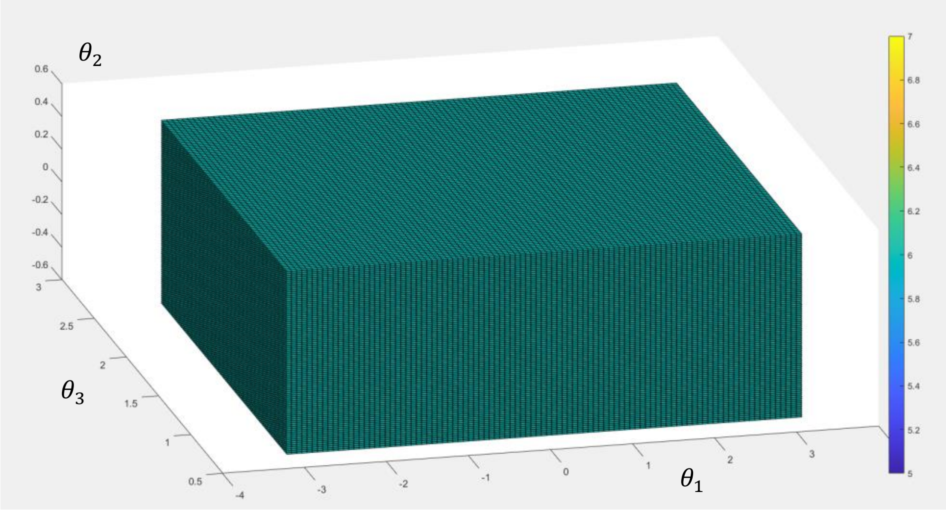


Figure 29 Plot W_z end-effector velocity, z-component across workspace.

4.1.1.5 Acceleration Equation:

Taking the time derivative of velocity equation to obtain acceleration equation,

$$A = J * \ddot{\theta} + \left[\frac{d}{dt}J\right] * \dot{\theta}$$

The end effector acceleration range was calculated over the workspace, by implementing the equations over a grid of workplace points (different initial conditions) and using maximum joint angle velocities and acceleration. The maximum end-effector accelerations were noted for the torque calculations:

Plots:

Following plots and results were obtained to note maximum values:

Acceleration component (x-axis):

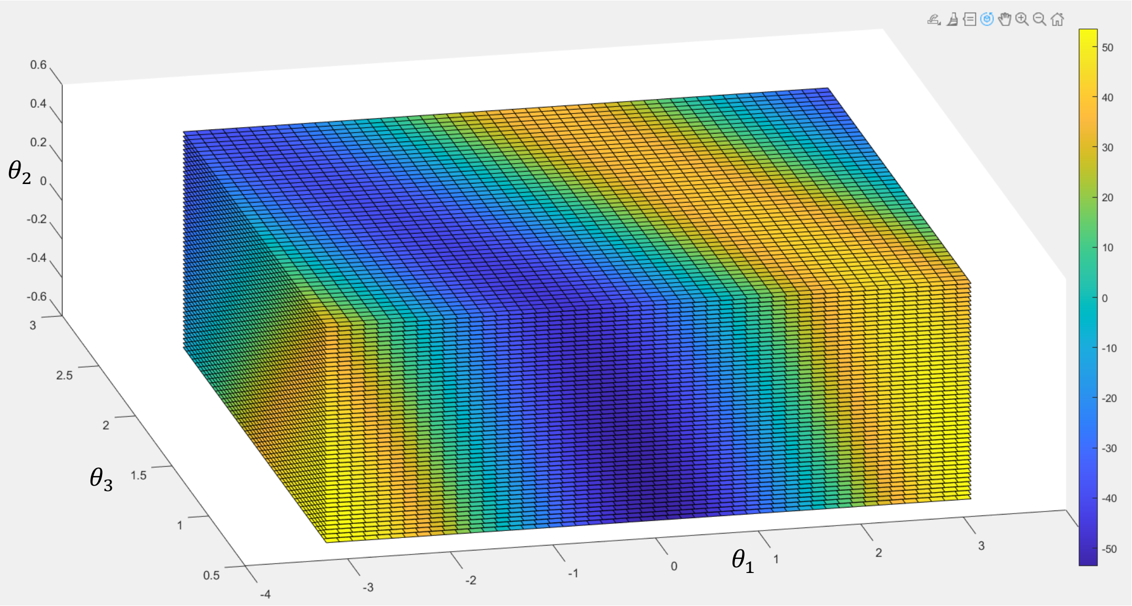


Figure 30: Acceleration Plot x-Component

Acceleration component (y-axis):

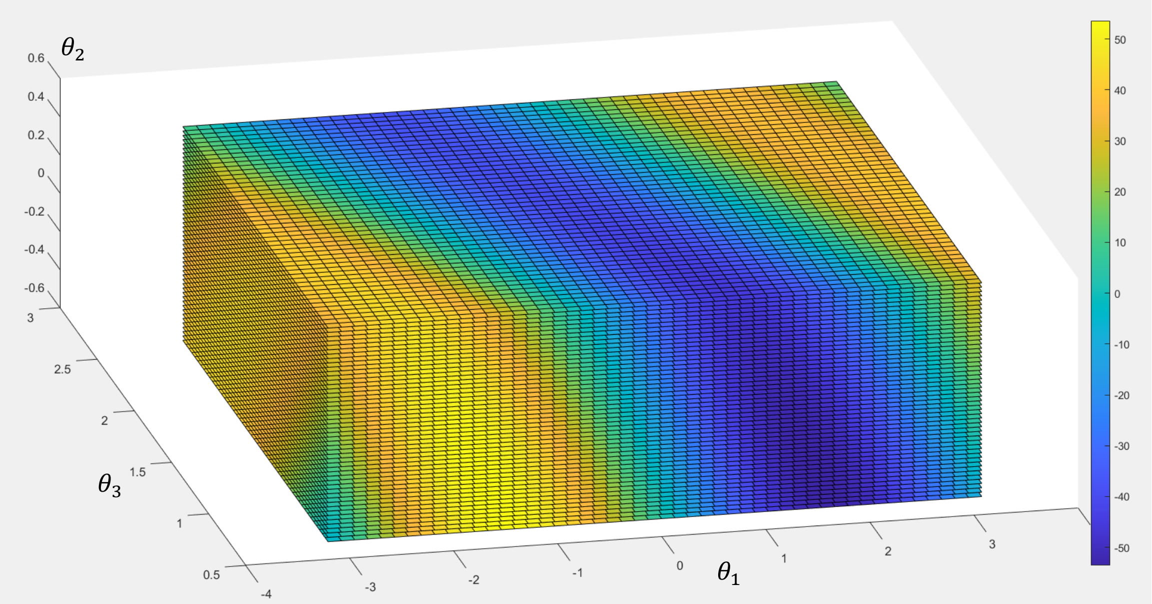


Figure 31 Acceleration Plot y-component

Acceleration component (z-axis):

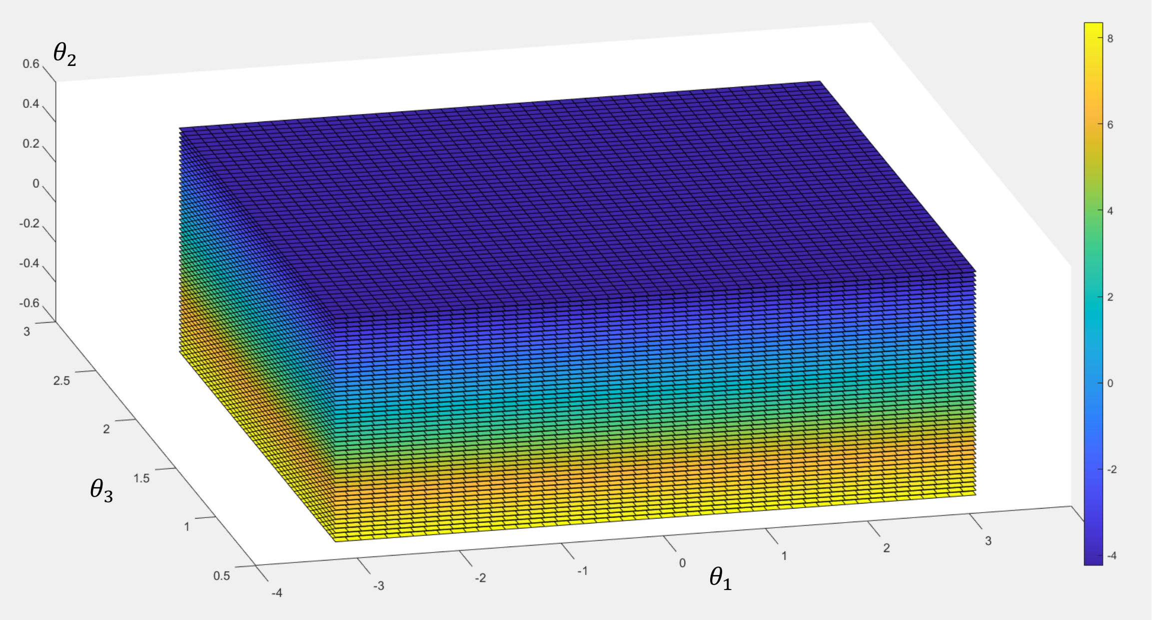


Figure 32 Acceleration Plot z-component

Pose Acceleration component (z-axis):

$$\dot{\omega} = 7.5\, rad/s^2$$

4.2 Kinetics and Torques:

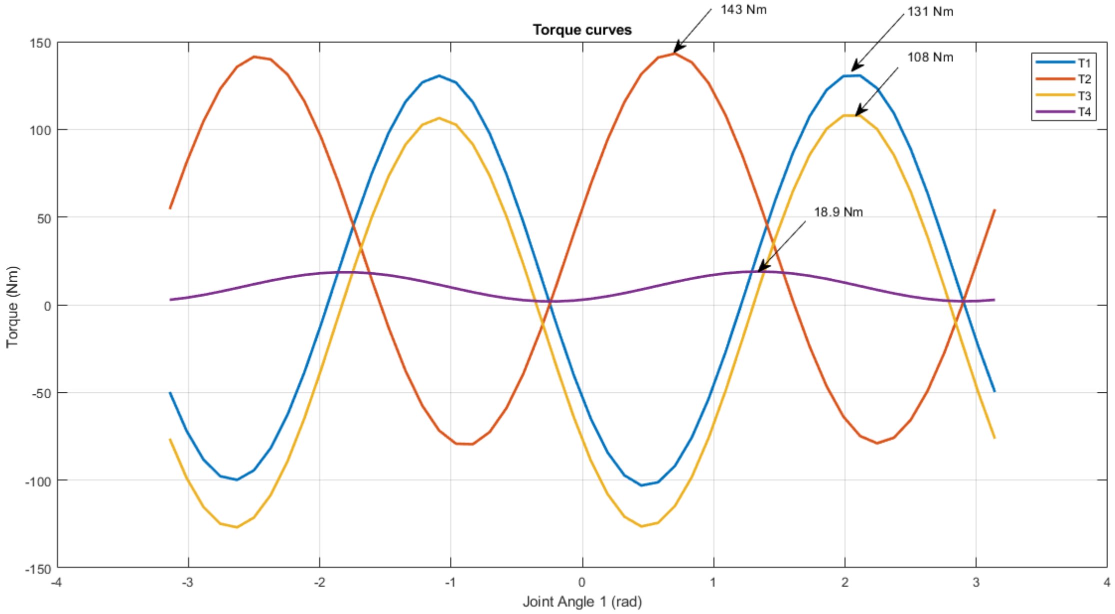


Figure 33 Torque Plots

The graph shows the maximum value of joint torques required at each of 4 joints.

Table 2: Mathematical Model

Joints	**Maximum Joint Torque Provided (Nm)**	**Joint Torques Required (Nm)**	**Joint Velocity ($\dot{\theta}_i$) (rad/s)**	**Joint Angles θ_i (rad)**
1	180	131	2.5	$-\pi < \theta_1 < \pi$
2	150	143	3	$\frac{34\pi}{180} < \theta_2 < \frac{146\pi}{180}$
3	130	108	3.5	$-\frac{8\pi}{45} < \theta_2 < \frac{8\pi}{45}$
4	23	18.9	20	unlimited

The table shows a comparison of maximum torque which can be provided by motor when running at required speed and the maximum value of joint torques required. All required torque values are below provided torques. Hence, we are within safety limits. Thus, we conclude that motor selection is successful.

4.3 Prototype

4.3.1.1 Robotic Arm

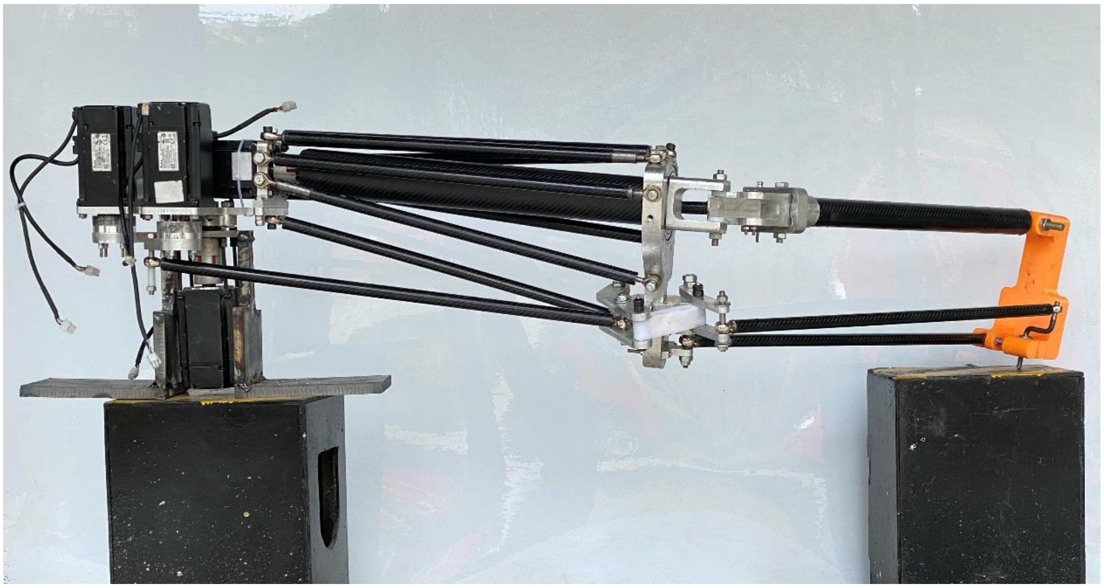


Figure 34: 4 DOF Robotic Arm Prototype

4.3.1.2 Bill of Materials

Table 3: BoM

Material	Unit	Unit Price	Qty	Total Price (PKR)
Aluminium	kg	3,500	17	60,000
Motors	#	100,000	4	400,000
Carbon Fiber 22x18	#	3,000	7	21,000

Carbon Fiber 64x60	#	60,000	1	60,000
Carbon Fiber 44x40	#	20,000	2	40,000
Nut Bolts	#	100	100	10,000
Rod Ends	#	650	18	11,700
Steel	kg	375	20	7,500
	Total			**610,200**

CHAPTER 5: CONCLUSION AND RECOMMENDATION

The literature review suggests that this robotic arm has some other similar designs. The majority of these models are six-axis robotic arms, which offer great levels of precision and accuracy for a variety of applications. The utilization of sophisticated mechanical and control systems, AC servo motors, and closed-loop feedback systems for precise and fluid movement are shared characteristics of these devices.

The reach and payload capacities of these devices varied significantly, and depend on the particular application. In addition, some designs employ various end effectors to accommodate various purposes. These designs also range in terms of the software interface, with some utilizing graphical user interfaces and others utilizing programming languages like C++ and Python.

This robotic arm is a competitive design that offers a high level of performance and versatility for industrial applications, according to the literature review as a whole. It is a useful instrument for applications that need great accuracy and repeatability thanks to its distinctive qualities, like the lightweight and strong aluminum alloy frame. The performance of the arm can be examined through additional investigation and testing in a variety of settings and applications.

5.1 Comments

The robotic arm design offers a new, fourth motion principle for quick pick-and-place with its distinctive, patented arm arrangement. It is constructed with fewer degrees of freedom and performs better for pick-and-place applications than current scara, delta, and standard 6-axis robots. [6]

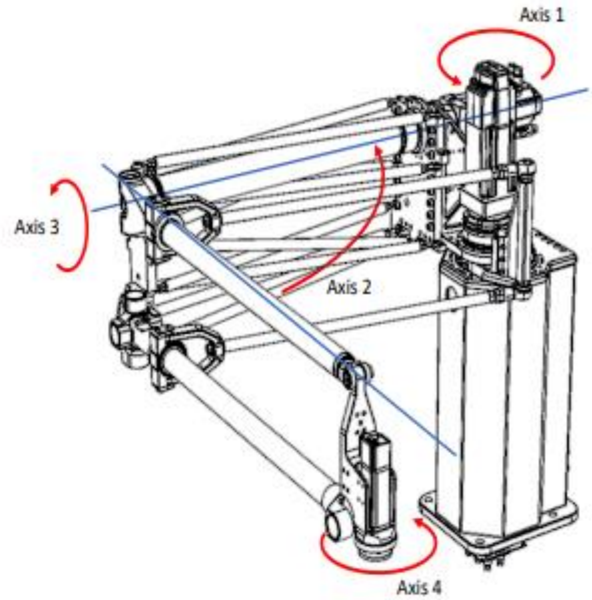


Figure 35 Four degree of freedoms of Robotic Arm

The robot will be one of the quickest robots on the Pakistani market and will offer an unheard-of mix of rigidity and light weight thanks to its construction using high strength, low weight components. The energy usage is extremely low because the fixed base of the manipulator holds 80% of the manipulator's weight. The arm uses light weight aluminum and carbon fiber tubes. This reduces the weight immensely.

Without the requirement for supporting structures, the long reach enables you to replace multiple traditional robots to serve several pick-and-place locations.

The aim of the project is to achieve the following outcomes:

5.1.1.1 Ideal pick-and-place robot

The robot is perfect for pick and place applications due to its long reach and rapid speed. A single robot may handle numerous pick and place stations and cover enormous areas all at once. The robot's thin form even enables it to fit into shelves and may be put on the ground, a wall, or the ceiling.

5.1.1.2 Processing materials quickly

The robot's light weight enables it to move quickly across its full work space, including an astounding z-stroke of nearly 1 m. It makes the most of its quick cycle time of 1-2 seconds by conveniently serving many machines. Because of this, it is perfect for material handling duties when there is a great deal of space between various work stations.

5.1.1.3 To replace several others with one robot

The robot can take the place of multiple conventional robots because of its speed and coverage. As a result, production lines can be smaller and take up less floor area. Moreover, it gives the robot the ability to work both upstream and downstream of a material input and dynamically track a moving object for processing.

5.1.1.4 Usage of less energy

An energy-efficient robot is designed. Since the robot arm weighs so less, its movement requires the least amount of energy. As a result, it can quickly accelerate and decelerate without suffering significant energy losses or producing excessive heat. Because of this feature, robots may be utilized in collaborative settings and are extremely quick at the same time. Also, it lowers energy costs and makes installation processes simpler.