Design and Analysis of the Spray-Painting Robot for Tower

By

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Design and Analysis of the Spray-Painting Robot for Tower

Major Project Report

for Semester-IV

Master of Technology in
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(CAD/CAM)

Submitted by
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Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering (CAD/CAM) at Nirma University and has not been submitted elsewhere for a degree / diploma.
2. Due acknowledgement has been made in the text to all other material used.

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I, **Dipen Detharia(19MMCC04)** gives undertaking that the major project Entitled **“Design and Analysis of Spray-Painting Robot for Tower”** submitted by me, towards the fulfilment of the requirements for the subject “Major Project” in the Mechanical Engineering of Nirma University, Ahmedabad, is the original work carried out by me. I give assurance that no attempt of plagiarism has been made. I recognize that it would result in significant disciplinary action in the event of any similarity identified subsequently with any published work or any dissertation work elsewhere.

Signature of student:

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Place: Ahmedabad.

Endorsed by:

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Certificate

This is to certify that the Major Project Report entitled, **"Design and Analysis of Spray-Painting Robot"**, submitted by **Mr. Dipen Detharia(19MMCC04)**, towards the fulfillment of the requirements for Semester-IV of Master of Technology (Mechanical Engineering) in the field of Computer Aided Design and Computer Aided Manufacturing of Nirma University, is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion, reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Dipen Detharia

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Abstract

The Telecommunication industry plays an important role across the globe for social communication, national security, and connectivity for 24x7x365. Considering most of the cases for maintenance of the telecom towers, the conventional methods are used for maintenance work. Generally, highly certified riggers (human laborers) are being sent on the towers for maintenance purposes risking their lives in danger. As robotics has found its application in both structured and unstructured environments but still there some sectors it requires to do automation it involves the telecommunication industry. But there are some hazardous incidents are occurring on telecommunication sites while performing maintenance of telecommunication towers. Due to COVID-19 online culture is developed due to which payload is also increasing turns in increment of maintenance work Also, the rate of accidents and subsequent work on height hazards increase. The maintenance involves inspection, antenna erection, antenna painting, to check the proper connections, etc. But spray- painting of telecommunication antennas are distinctive representatives of the thesis.

The Foremost aim is to design a manipulator for spray painting of an antenna; which should be light in weight as it will be mounted on the top of the structure climbing robot and can be easily accommodated within the workspace of the tower. While designing the manipulator design considerations, the actuation of the manipulator, material selection is the important parameters. The robotic manipulator of 6 kgs with RRRP configuration i.e., four degrees of freedom, with Acrylic; the plastic alloy as the material is designed in Solidworks2021.

Denavit-Hartenberg algorithm for link and joint is used to prepare the direct or inverse kinematic model for the robotic manipulator. By establishing the rigid body tree model in Robotics System Toolbox, the numerical model of direct and inverse kinematics using Homogenous Matrix Transformation is prepared in MATLAB as it is tedious equations to solve analytically. Through the spray patch method and offline programming method, the spray model is prepared in Solidowoks2021 by giving the input variables appropriately and obtain the waypoints. Through the Joint Space Technique, the B-spline trajectory is

generated through these waypoints where at each waypoint joint displacement variables are obtained with the help of inverse kinematic model in Robotics System Toolbox, MATLAB. With the help of the airless spray gun which will be clamped and it will be controlled with the help of PLC. Electrical Motors are controlled with the help of the Arduino which will be operated through Wi-Fi, camera vision, and the teach-pendant motion can be controlled. Therefore, kinematic analysis and trajectory generation fulfil the aim of the spray-painting of the antenna. Thus, the simulation of the manipulator shows that it follows the defined trajectory properly.

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Abbreviations

dof	Degree of Freedom
DH	Denavit-Hartenberg
HT	Homogeneous transformation
R	Revolute
P	Prismatic
H	Quaternion vector
COG	Centre of Gravity

Nomenclature

a_i	Link Length
α_i	Twist Angle
d_i	Joint Distance
θ_i	Joint Angle
c_i	$\cos\theta_i$ (i=1,2,3…. n)
s_i	$\sin\theta_i$ (i=1,2,3…. n)
T	Transfer Matrix
O	Origin of Global Coordinate System
$O_{1,\,2\ldots3}$	Origin of Local Coordinate System of Frames
$q_{\,1,2\ldots3}$	Joint angles of the model

Chapter- 1

Introduction

The introductory chapter offers an insight into the rationale of the subject of the study and incorporates several concepts that are relevant to it. The chapter also aims to take up this thesis work and the framework followed here to present the same, following a fundamental introduction into several aspects of the telecommunication sector and its problem related to maintenance of tower, fatal-fall of riggers from the telecommunication towers while maintenance, spray-painting manipulators as it is an application which is focused on, and fundamentals of robotics for designing the manipulators.

1.1 Project Inspiration and Background

For supporting system into our lives, it requires the transformation of social and living environment. The key technologies to achieve the supporting system are Mechanical, Electronics, and Informatics. A robot manipulator insinuates an electrochemical device that involves human agility to perform a variety of tasks. To implement in our daily lives' manipulators should meet some basic conditions like compact, lightweight, safe and inexpensive. However, it is very difficult to achieve all the basic conditions together. Further studies are carried out to achieve the working of the robot, weight of the robot but still not satisfied to meet all the basic conditions.

For the past two decades, in each field robotics has advanced prominently. For achieving uniform quality in each field, to increase productivity industries are rapidly transforming from automation to robotization. Of the robots available in the world, 90% are deployed in industries and 50% are deployed in automotive industries [1]. According to the reports of the Indian Federation of Robotics (IFR) [2], the supply of the industrial robot is increasing rapidly as shown in Figure 1.1.

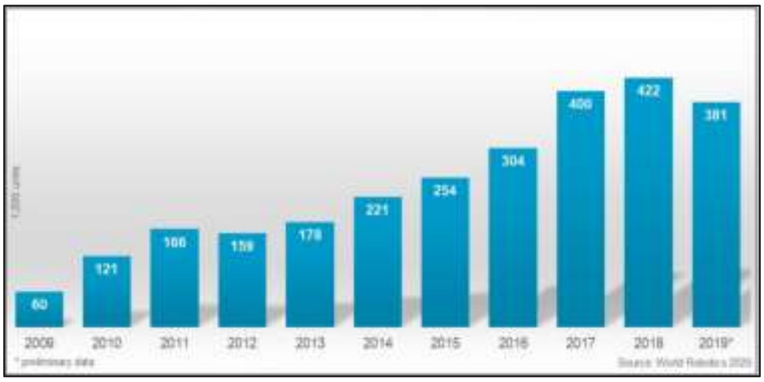


Figure-1.1 Annual Supply of Industrial robot

Robots and robot manipulators have been employed in a broad range of applications such as planetary space exploration, surgical robotics, rehabilitation, and household applications. There is some common characteristic of such applications is that the robots need to operate in unstructured environments rather than structured industrial work cells.

In hostile environments powerplant, medical surgeries, to construct and repair space satellite, on-field activities in the telecommunication maintenance; need of robotic arises so robot and robot-like-manipulator are frequently hired. Robotics has prominently in all the sectors and there are still some sectors like telecommunication sectors where human risking lives and repetitive tasks which incorporates robots in applications.

Telecom Services are the portion of essential services, which companions the community in effective manner and helps to make communication comparatively faster. The tele-communications industry is broader than it was in the past years. It encompasses multiple service providers, including telephone companies, cable system operators, Internet service providers, wireless carriers and satellite operators. The industry nowadays includes software-based applications accompanied with a communication emphasis and intermediate layers of software, incorporated into end-to-end communication services. It also includes suppliers of telecommunication equipment and software products sold directly to consumers and also to service providers, including the telecommunications service providers.

The increasing demand for communication payload has led to a tremendous increase in the number of telecommunication towers and the task of maintenance of it becomes very crucial with limited skilled manpower nearly almost 5.5 lacs towers; requires 1 lakh skilled manpower and 10 lakh more by 2027 for fulfilling demands [3]. According to the case study of by the “Mobile Network” in telecommunication services site riggers jobs are becoming more complex which refers it has to carry 20 instruments as payload for maintenance as shown in Figure 1.2[4].

Figure-1.2 Tower Rigger

Telecommunication towers have heights variants from 100 to 2150 feet and more as shown in Figure –1.2 [5] due to this the job of riggers has become most dangerous and pressurized. The maintenance of various equipment of the tower requires frequent climbing on the telecommunication tower 4-5 times a day as per a technician which includes the fatality incidents from the tower.

Figure-1.3 Maintenance work performed by riggers

The major challenges and issue associated to telecom tower maintenance include: work at height hazards (fall due to breaking of harness hook or belt, birds hit, electric shock), climbing frequency increases as communication payload increases, most of the activities require full body extension.

There are various types of climber robots available for inspection purposes on the heights like chemical tan inspection, crack detection in nuclear reactors, pressure vessel testing, construction robots, and pipe climbing robots. But these theses are special representatives of designing the robust manipulator for spray-painting of antennas. A manipulator will be mounted on the platform of the tower climbing robot as shown in Figure-1.3 [6] which allows performing the spray-painting task as well as inspection.

Figure-1.4 Servo-controlled robotic arm

1.2 Importance of Telecommunication Sector

1. Telecommunications and Society: The societal importance of telecommunications is well accepted and broadly understood, reflected in its near-ubiquitous penetration and use. Noted below are some of the key areas of impact:
    - It provides a technological foundation for societal communications.
    - It enables participation and development.
    - It provides vital infrastructure for national security.
2. Telecommunications and the Indian Economy: The telecommunications industry is a major and direct contributor to Indian economic activity. Telecom industries contribute 3.3% of the Indian GDP.

3. Telecommunications and Global Competitiveness: In this era of globalization, many companies are multinational, with operations including R&D, conducted around the globe. For example, IBM, HP, Qualcomm, and Microsoft all have research facilities in other countries, as well many European and Asian companies have research laboratories in the United States.

In the highly expanding field of the telecom industry maintaining a network for connectivity, tower troubleshooting task (Telecom site maintenance) is done manually over the globe. It is highly demanded to introduce RIA in operation due to the following reasons.

1.3 Need of Automation

The key highlights [7] associated with Indian Telecommunication Sector are:

- Across the globe, India upholds its rank as second in terms of the number of telecommunication subscriptions, internet subscriptions, and downloads.
- With 70% of the population staying in rural areas and a telecom penetration rate of 58.45%, the rural market will be the key growth driver.
- The Government of India unveiled the national Digital communications policy & aimed to attract approximately 100 billion dollars investment.

The maintenance of telecom equipment is the key to ensuring up the time of telecom network and effective customer experience. According to reports from the Department of Health and Human Services (USA) [8] in 2001 identifies work of telecommunication maintenance has a higher rate of fatality. From 1992 to 1998, 118 deaths were associated with telecommunication towers which include 93 falls, 18 tower collapses, and 4 electrocutions.

In India According to the data of fatal falls in 2012; tower climbing an obscure field with several more than 10,000 workers, has a death rate roughly 10 times that of construction sites [9]. The following figure from Figure-1.2 to Figure-1.5 shows the maintenance operation taking place on different types of towers.

Different types of towers majorly include Ground Base Mast and (GBT) and Ground-Based Tower (3 and 4 Legged) ranging from 25 to 30 meters high. [10]-[12].

Figure-1.5 Rigger attached with truck crane and hoist

Figure-1.6 Riggers climbing the tower with payload

Figure-1.7 Fire on top of the tower

Figure-1.8 Maintenance on top of four-legged tower

A few contributing factors in fatal falls from telecommunication towers are:

- Failure of host
- Truck-crane failure to attach the lanyard to the tower
- Inadequate worker training
- Repetitive strain
- The payload on the workers.
- Terminal gadgets on the lanyard which are not compatible with tower components
- Highly regionalized and manpower-intensive operations
- Lack of operational visibility indirectly affecting long-term planning and strategic improvements.

This project it will be focused on the designing the light weight manipulator for application of spray-painting of tower antenna as shown in Figure-1.6[13]. The requirement of painting the refractory paint on the towers and antenna arises because it can be visible the presence of tower and avoid the corrosion. Apart from corrosion these the antenna is painted frequently to transmit the signals properly.

Figure-1.9 Robust Manipulator

1.4 Problem Statement

With the consideration of the highly competitive telecommunication sector of today's world, to overcome the fatal falls and effective completion of predefined tasks; requirement arises to perform automation. While considering the review of telecommunication professionals; it is envisaged that telecommunication equipment maintenance is possible with Robots. So, robots can effectively and remarkably perform some of the key activities either active or passive activities.

Various types of activities are required to be performed on the top of towers like checking connections, measuring connectivity, rectifying alarms, spray-painting of the antennas and tower poles, to throw the fire-balls when the fire is caught on the top of the tower. The aim herein is to design the manipulator which will be mounted on the base of the tower climbing structure which can do the task of spray painting of the antennas; as frequent spray-painting is required for the better connectivity and resistance from the corrosion for particularly monopole type of tower structure.

1.5 Objectives

- To design the robotic arm for the spray-painting of the antenna.
- To develop a forward and inverse kinematic analysis model of the arm.
- To generate trajectory planning for spray painting of antenna.

1.6 Structure of Thesis

Chapter-1: This chapter contains an introduction about the importance of telecommunication industries, problems faced by tower riggers, fatal falls, maintenance of the tower.

Chapter-2: This chapter gives an overview of articles that were referred during this project work and how those articles were helpful to the given project.

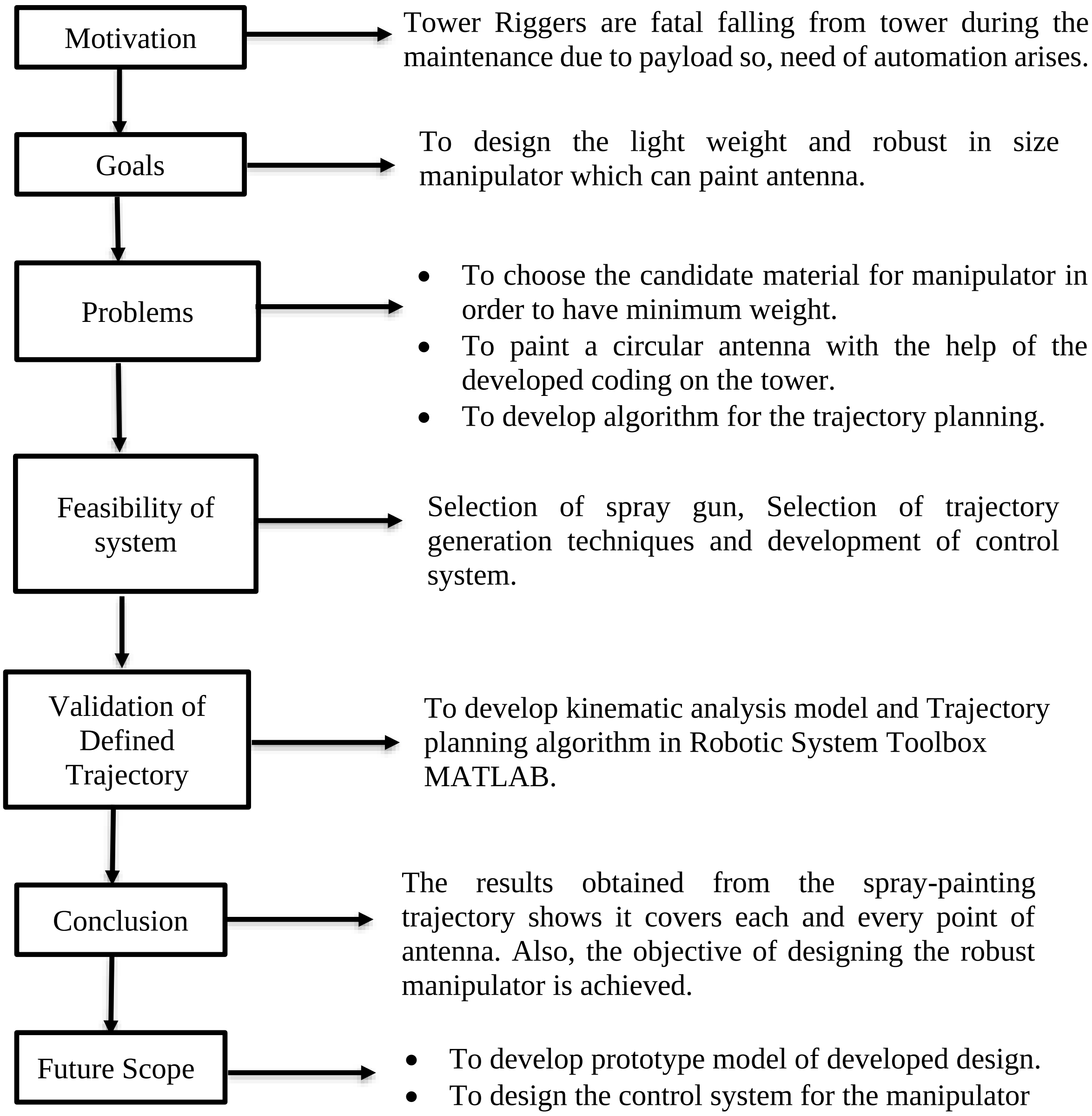
Chapter 3: This chapter contains important considerations for design of the manipulator; design of manipulator parts, assembly in Solidworks 2021. It also describes procedure for selection of material for robotic manipulator, actuator, control system.

Chapter 4: This chapter contains mathematical modeling of four-degree of freedom manipulator is discussed which includes kinematic modeling i.e., forward kinematics and inverse kinematics modelling of the manipulator.

Chapter 5: This chapter begins with describing the terminology involved in trajectory planning, steps to generate trajectory planning, generates a trajectory for spray painting of antenna, contains the rigidBodyTree model, trajectory model, inverse kinematics model code is generated in MATLAB.

Chapter 6: This chapter discusses the results and conclusion obtained from the trajectory generation of sprat-painting manipulator and further also discusses the future-scope of the project.

1.7 Flow of Research



Chapter 2

Literature Review

The literature review of the fatal falls from telecommunication sector and industrial robots for spray-painting looks up-to-date how the research provides a significant contribution. This chapter follows the history of the designing the manipulator according the type of antenna and tower and by taking motivation from industrial spray-painting robot an overview of the robot is developed in order to design the robot and follow the trajectory for spray-paint of the antenna.

2.1 Literature Survey

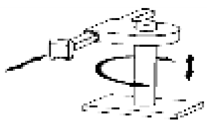
Department of Health and Human Services [8] In 2001 reports deaths which are resulting from falls during construction and maintenance of telecommunication towers. Through the Bureau of Labour Statistics in United States which identifies work on telecommunication towers shows the rate of Fatality is high. Also, 118 deaths associated with work on telecommunication tower from 1992 to 1998 which includes 93 falls, 18 tower collapses and 4 electrocutions.

In 1993, estimates ranged from 2300 to 23000 workers in this field. It estimates fatality rates of 49 to 468 deaths per 100000 workers which nearly 10 to 100 times average rate of 5 deaths per 100,000 workers. It identified some contributing factors sin fatal falls from telecommunication towers are hoist failure, truck-crane failure, Inadequate fall protection, inadequate worker training, potential fatigue, failure to attach the lanyard to the tower.

Safety Management Group [14]- SMG is one of America's largest safety company which is held privately which provides consultancy assistance. According to SMG reports, at one of recent conference, OSHA administrator David Michaels said that workers on communications towers face a significantly higher rate of onsite deaths – which is reported as 25 to 30 times the normal rate. As riggers requires to lift mechanical equipment 100 to 1000 feet or more, so payload increases which leads to fatality. Apart from these parameters also the climate, skills, state of mind also plays an important role.

Mittal and Nagrath, Robotics and Control [1] Basic configuration on the basis of workspace:

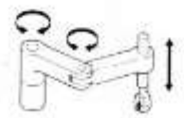
(a) Cartesian Configuration



(b) Cylindrical Configuration

(c) Polar Configuration

(d) Articulated Configuration



(e) SCARA configuration

Figure-2.1 Basic configuration of robot

Types of Antennas [15] There are two types primary antennas used in mobile tower: rectangular antennas; circular antennas. Each rectangular antenna will be able to cover an area within 120 degrees and three different antennas are placed facing in all the three different directions while circular antenna is interlinked in direction to get stringer network.

Figure- 2.2 Rectangular Antenna

Figure- 2.3 Circular Antenna

According to Spray System inc. [16] describes a variety of different types of spray-painting methods which currently in use:

- Air-atomized
- Airless
- Electrostatic
- High-volume, Low-pressure

Air-atomized painting is one of conventional approach, where compressed air is used with spray gun to coat the surface. It has poor transfer efficiency as compared to other approach. Airless painting is very compact in setup while electric spray gun is highly efficient. The main advantage is that it does not contain air bubbles so therefore it covers large spray volume.

Paul and Zhang [17] proposed kinematic analysis of manipulators with spherical wrists by describing its position and orientation through homogenous transformation. They used proposed technique to obtain kinematic equation directly suitable for computer implementation. The resulting equations include the least number of mathematical operations.

Aspragathos and Dimitros [18] discussed the three methods for the preparation of the kinematic equations of robotic arm with rigid links. In first and most conventional method in the robotics on the basis of homogenous transformation, the second one is based on Lie algebra, and the third one on screw theory stated with dual quaternion algebra. The evaluation of these three methods are used in the kinematic analysis of robotic manipulator. Three different analytical algorithms are prepared for the solution of forward kinematics problem. However, it is concluded that it cannot be used for higher degree of freedom.

De Xu [19] proposed an analytical solution for a 5-dof manipulator to follow a given trajectory while keeping the orientation of one axis in the end-effector frame. Forward kinematics and inverse kinematics are used for 5-dof manipulator. The singular problem is discussed after the forward kinematics is provided. For any given reachable position and orientation of the end-effector, the derived inverse kinematics will provide an accurate solution. In additional, there exists no singular problem for the 5-dof manipulator, which has varied application areas such as welding, spraying and painting. Experiment results validate the productivity of the methods developed in this paper.

Kucuk and Bingul [20] proposed forward and inverse kinematic model for serial manipulator on the basis of homogenous transformation. Also, geometric and algebraic approaches are discussed with the explanatory examples. Apart from these direct and inverse kinematics transformations are derived on the basis of quaternion modelling convention.

Nielsen [21] has represented solution techniques of inverse kinematics using polynomial continuation, Grobner bases and elimination. They compared the results that have obtained with these techniques in the solution of two basic problems namely, the inverse kinematics for serial-chain manipulator and direct kinematics of in-parallel platform devices.

Daniel, Lupoae, Catlain, Buliga [22] has accepted out the forward kinematic analysis i.e., analytical and numerical of six dof industrial robot arm. The manipulator provides a payload of 5kg capacity and it can reach of 704mm with electric six servo driven motors. It formulates D-H parameters which characterizes analytical method to locate the position and orient it. Further in Robotics System Toolbox for MATLAB allows to simulate the robot. It concluded that numerical values of the software and teach pendant were practically validated. It will intend the future research on Inverse Kinematics, Jacobian and dynamics of the robot.

Jamshed, Raza, Hamza [23] has represented forward kinematic model is predicted on DH parametric scheme of serial robot arm position placement. It implements the analytical obtained parameters from D-H parameters into MATLAB software for joint configuration. Workspace of a robot enables information Range of Motion (ROM) of joints of robot and links. The simulation results verify that results obtained from software and real robotic platform have ±0.5cm.

Perez and McCarthy [24] proposed dual quaternion algebra based kinematic synthesis of constrained robotic system containing one or more serial chain manipulator for both revolute and prismatic joints. For obtaining joint variables of an end effector position D-H algorithm and successive screw displacements method is used. With the help of dual quaternions, the transformation matrices obtained through D-H algorithm to simplify the design formulation of different types of manipulators.

Hanming Cai1 and Xing [25] proposes the kinematic simulation of the six degree of freedom industrial robot where modelling is carried out in Pro-E. D-H transformation

Method is used to establishing the kinematics model and the target matrix in MATLAB. The Workspace is defined as position flock which specifies parts of the manipulator which can be achieved under certain conditions. From its shape and size, it reflects the workspace analysis of the manipulator as shown in the Figure- 2.17. For analysis of workspace Monte Carlo Method is used. In Monte Carlo method, probable model is prepared to reach the given constraints.

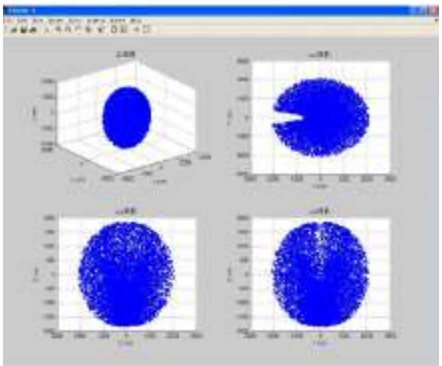


Figure-2.4 Workspace analysis of 6 dof manipulator

Cholewa Sekala, Swider, Zbilski [26] has carried out the Forward kinematics of industrial Fanuc AM 100iB with six degrees of freedom which has spherical workspace. It assumes orientation of the local coordinate systems and modifies Denavit-Hartenberg parameters. With analysis of classical algorithm, a kinematic model of the robot is prepared in MATLAB Simulink software as shown in figure 2.5.

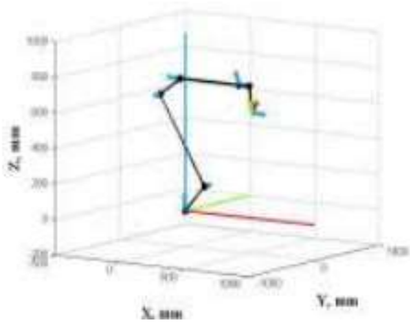


Figure- 2.5 Model developed in Robotic System Toolbox

The dynamic model of the robot is prepared in the form of a block diagram using SimMechanics toolbox as shown in figure-2.6. It verifies its values from the actual robot, results in limited verification of the dynamic model of the analyzed device. Further it enables to carry out research on the development of energy-efficient trajectories.

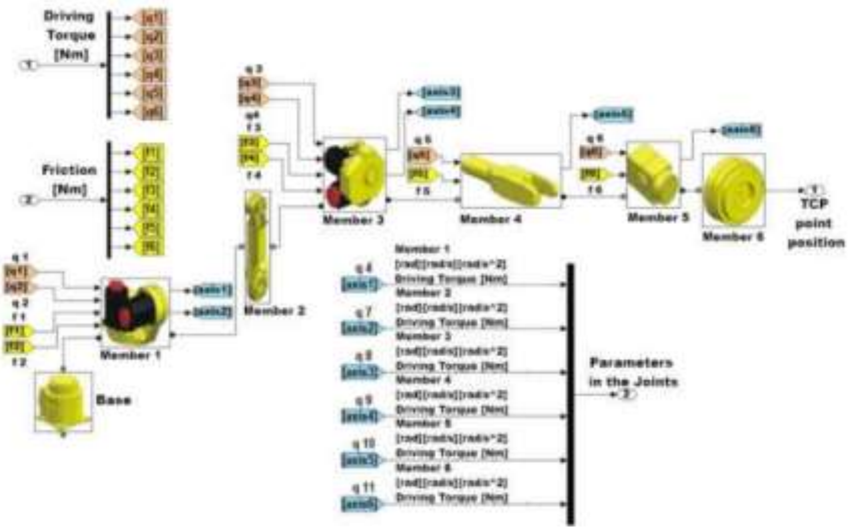


Figure-2.6 Block Diagram of Numerical model in Simulink

Ruthber Rodriguez Serrezuela [27] proposed the design and implementation of kinematic model for the robotic arm with four degrees of freedom. The paper proposes the model performance which are checked mathematically using DH parameters, allows to govern robot joints angle vector. For checking the direct and inverse kinematics was developed in the MATLAB, Botbarduino using a card like interface, which allowed AL5A, position the Robotic arm at points X, Y, Z and mathematically calculate the angles.

Parham Kebria [28] proposed mathematical kinematic, dynamic, MATLAB, SimMechanics models for the UR5 robot. The kinematic characters were implanted in the MATLAB further robot's dynamic properties, inertia matrix, Collioris and centrifugal matrix and gravity vector were calculated on the basis of Lagrange method. After that SimMechanics model shows that position and orientation profiles were tracked chosen while the state of system was stable.

Dongkang He [29] proposed the optimal design of PUMA560 robot as research object, it uses D-H coordinate transformation method to obtain the positive kinematics equation expressed by poison vector and Euler angles. The workspace of robotics refers to all positions that could be solved by the end effector of the robot. Through the Inverse Kinematics equation, Singularity positions and postures in the workspace are decided and normality of the robot is checked in Robotic System Toolbox.

Gujela [30] have probable the analysis model of six degree of freedom robot for spray-painting with the support of the Denavit-Hartenberg method for forward and inverse kinematics to find the relation amongst the joint angles. Spray painting patch is generated on the regular shape work-piece with the help of MATLAB. Further measurement is carried out in Solidworks software.

G. Krishna [31] have proposed generalized code for Forward Kinematic Analysis of 5-Axis Articulated Robotic Arm by using the MATLAB programming. With industrial evolution, there is need of low-cost robotic platform which is operated remotely through the gripper and control data. Its emphasis on the Forward Kinematics, which evolves on defining the target point with the help of the joint angles of the revolute joint and coordinates of the prismatic joint. While Inverse Kinematics involves finding out the different possible solution. Also, it become tedious as it gives more than one solution manually. Therefore, they developed the generalized program to reach the target point.

Dr. Laith and Alaa Hassan [32] has proposed the relationship between the distinct joint of robot arm and the position and orientation of end-effector for R5150 arm. It can be operated through teach-pendant with the input parameters from the programmer or either it can be simulated in RoboCIM software. Through D-H parameter's analytical scheme of the end-effector is performed through MATLAB in order to validate the behavior of the robot physically.

Guida and Simone [33] proposed different modelling techniques of "COMAU Smart Six 6-1.4" manipulator, which is produced by Italian multinational company Consorzio Machine Utensili for application ranging from heavy industrial, railway, automotive. It consists of 6 links and the motion is controlled by brushless DC electric motors; also known as electronically commutated motors. As these motors have various advantages: high power to weight ratio, high speed and electronic control.

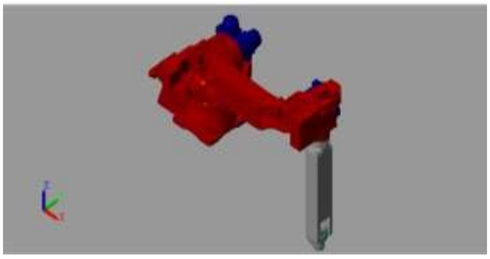


Figure- 2.7 Simscape Multibody Environment

The mathematical model is calculated with the help of D-H transformation matrix. CAD model is imported into Simscape multibody environment of Simulink which permits to simulate the operation of robotic arm as shown in Figure-2.12. Another model is prepared in Robotics Toolbox (RTB) for calculating kinematics program with the help of fkine function which will allows to calculate the kinematic equations. The comparison is made between two model and errors is in between 3 to 5% which is less than 10% hence it is validated.

Goyal and Seth [34] has proposed the analytical method for determination of workspace of robot. By defining D-H parameters of serial manipulator and then determining singular performances of each manipulator with the help of Jacobian method by the row rank deficiency condition. These singularities are substituted into constraints to obtain singular surfaces. In order to obtain three-dimensional space of the robot these singularities are substituted to combine all the singularities sets and plotted in MATLAB as shown in Figure-2.12.

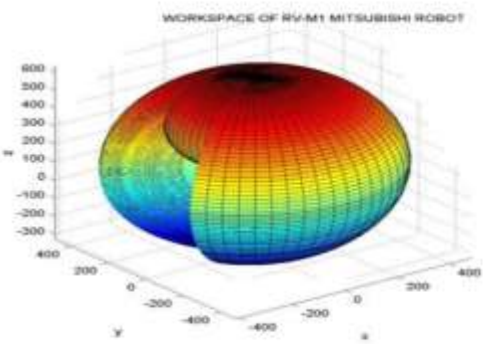


Figure-2.8 3-D workspace of RV-M1 Mitsubishi robot

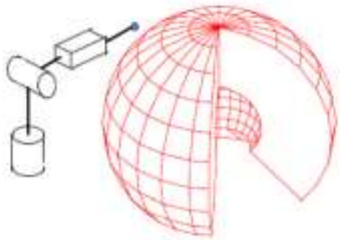


Figure -2.9 Workspace of RRP

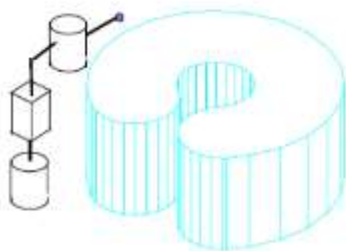


Figure- 2.10 Workspace of RPR

Low and Dubey [35] presented two different methods for inverse-kinematics problem for a six-dof robotic manipulator which are having three revolute joints. First method uses conventional generalized coordinates to describe the orientation and position of the end-effector. Second method incorporates with equivalent Euler parameters with one of constraint equation. And these two methods are in collaborated into two different algorithms in computer; further the results were compared and it was noticed that the Euler parameters were found less efficient than comparison of the three rotational angles for solving the inverse problems of the robot

Brandstotter et al. [36] presented an effectual general method for the solution of inverse kinematic of 6-dof serial manipulator. In this paper they have mainly focused on D-H algorithm with seven geometric parameters with joint angles.

Zengxi Pan [37] have proposed recent research progresses on the programming methods for industrial robots, including online programming, offline programming (OLP) and programming using Augmented Reality (AR). OLP methods which operate 3D CAD data of a workpiece to generate and simulate robot programs. It is widely used for automation system with large product volumes. In Figure-2.11some important steps are there to follow for OLP methods.

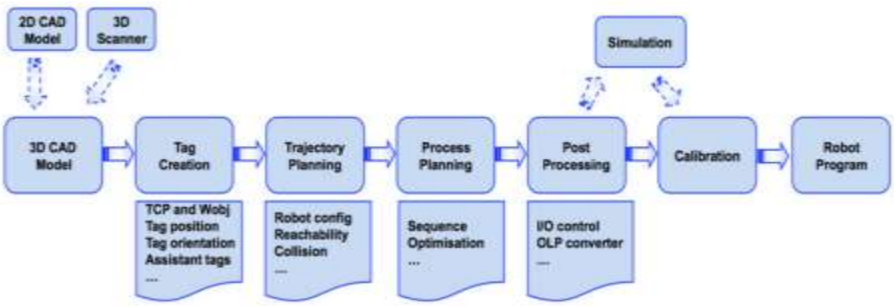


Figure-2.11 Key steps of OLP

Chen and Fuhlbrigge [38] have proposed the robot path planning based on the CAD models of parts for spray painting is critical for product quality, process cycle time and material waste. It describes about path generation related parameters of painting process, material deposition patterns, Automated paint path planning (APPP) methods, Computer aided tool planning method, Paint deposition simulation methods. It shows the different methods on Automated Tool path planning on the basis of parametric CAD models and tessellated CAD models.

Muzan, Faisal, Al-Assadu, Iwan [39] represents an industrial robot ABB robot model IRB1410 for painting applications. The Robot is designed and further D-H parameters are prepared through the Forward Kinematics. The spray gun is used for spray-painting through hydraulic actuator and directional control valve. For operating of manipulator is carried out through Baseware OS which controls motion, development and execution of application programs communication.

Figure-2.12 Flex Pendant Teaching of the paths and target

Through sensors which collects information about the internal state of the robot.24VDC Omron relays was used, to send signal to the DCV indicates when to activate air compressor. Flex Pendant is used to control the IRC5 controller as shown in Figure-2.1. The Tool center point of the robot is determined and tested in Robot Studio. By performing several testing's, the desired result is obtained.

Alaa Hassan, Dr. Laith [40] represents robot trajectory in the bases of the ruled surfaces have been developed which simulates the spray-painting process by using Labvolt RoboCIM 5150 articulated robot. The position and orientation of each joint, through Inverse kinematics model is prepared through MATLAB software and it is delivered robot system to determine the vector of joint variables or kinematic parameters for robotic arm as shown in figure-2.3. Thus, it uses offline trajectory generation system for ruled surfaces for spray painting.

Figure-2.13 Robot Manipulator System

A ruled surface is a polygon mesh formed between the two defined boundaries. For defining the boundaries circle, arcs, points, 2D/3D polylines to define the boundaries. One-way mesh is created of straight lines between two boundaries. With the help of these ruled surfaces as shown in figure-2.4 the paint trajectories and desired position of the robot is obtained experimentally.

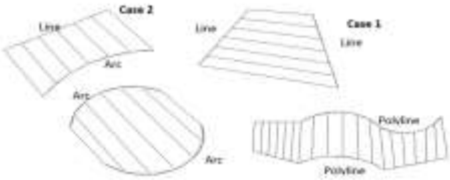


Figure- 2.14 Types of Ruled Surfaces

By generating the CAD model of the ruled surface, amalgamation the results of the inverse kinematics analysis of the robot and the trajectory of the robot. Simulation of the articulated robotic arm in MATLAB with the help of Lab volt R5150 Robot Manipulator System will leads to get experimental outcomes to fulfil the paint trajectory requirements.

Wang, Zheng [41] has carried out analysis on mechanical characteristics like force, mass, centroid, material, strength, stiffness of the body in order to achieve position accuracy. The three-dimensional model of the spray-painting in Solidworks and model is imported into ANSYS Workbench, and the static finite element analysis of the main parts. The model is imported into ADMAS simulation software to conduct dynamic characteristic simulation as shown in figure- 2.7,2.8 and 2.9. Virtual Prototype model is established and the drive and load conditions are applied which optimize the structure and control of robot, improves the motion performance of the robot.

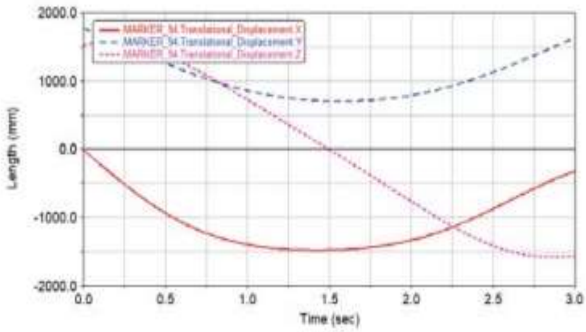


Figure-2.15 End displacement components of dynamics simulation of spray- painting

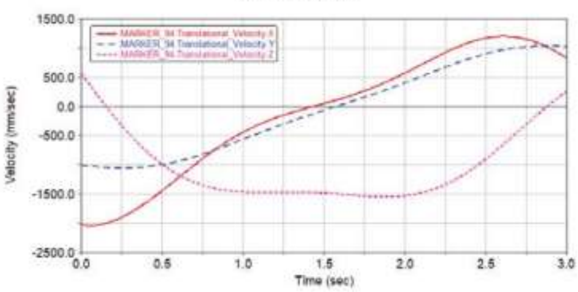


Figure- 2.16 End velocity components of dynamics simulation of spray-painting

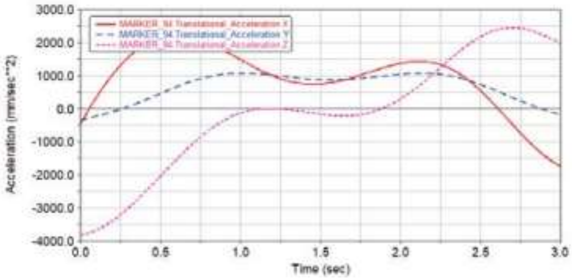


Figure- 2.17 End acceleration components of dynamics simulation of spray-painting

Arikan and Balkan [42] has proposed off-line programming of industrial robots for painting curved surfaces. It has recognized an algorithm and a computer program for modelling of the spray-painting process, simulation of the robot. Through the inverse kinematics solution algorithm data of joint space is obtained. It uses triangular mesh are generated which allows to spray on the requires surface area. Experiment is performed by using FANUC Arcmate Sr. industrial robot and BINKS 95-A Spray gun is used. It concludes amount of deviation will increase as overlapping increases.

Heping Chen [43] presents CAD-guided paint gun trajectory generation system for a freeform surface. This paper focuses on the patch generation algorithm to minimize the unconventionality angles of the spray cone. The combined trajectory is generated by optimizing the gun velocity and overlap percentage in painting process of a plane. The algorithm was implemented in C++and further simulated in ROBOCAD to simulate the painting process. Here paint distribution rate is constant instead of parabolic curve.

Yan Chen [44] proposed coating uniformity model which optimizes painting robot trajectories with assuming uniform robot motion and a parabolic spray distribution with uniformity evaluated based on the thickness variation. Overlapping distance should be taken into account to plan robot trajectory for spray painting. Dimensionless calculation results show that overlapping distance is a major influencing factors of mean coating thickness and the seed path position. Minimum thickness variance is about 0.0025 if overlapping distance is between 0.29 and 0.31.

Andulkar and Marathe [45] have represented spray gun trajectory planning which follows offline trajectory generation to generate robot trajectory as shown in figure-2.10. Based on the triangulated model of a free form surface, integrated trajectory is generated. It uses the Pattern Search Optimization in Optimization Toolbox in MATLAB is used to find a local minimum error which gives minimum overlapping of the paint.

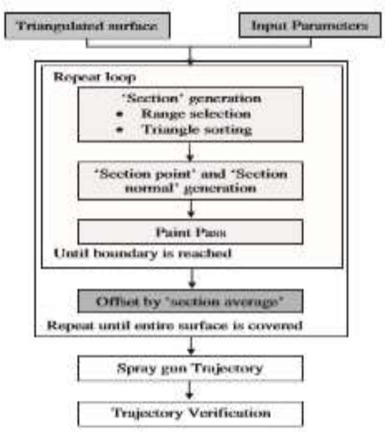


Figure-2.18 Integrated Trajectory Generation

An algorithm is generated for generating section creating the section point and section normal through which it will follow the trajectory until the boundary is reached by implementing the Raster pattern. The proposed algorithm was implemented in MATLAB and after verification it was performed experimentally on the robot. It concludes that characteristics of the spray gun plays an important aspect in obtaining the optimal paint distribution on any surface.

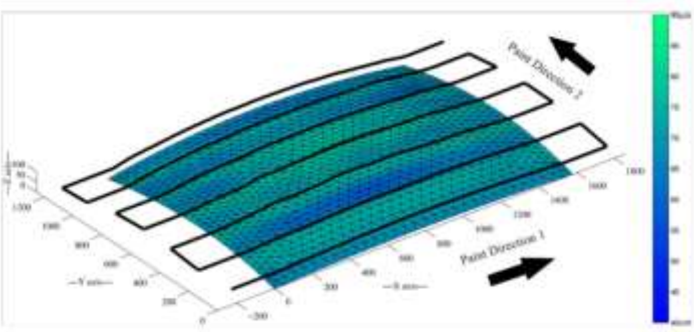


Figure-2.19 Trajectory for discontinuous raster pattern on car top (β=4)

Shuhuaa Lio and Li [46] uses PUMA560 as research robot in which it uses Robotic System toolbox and GUI programming environment of MATLAB, the specified function is called to simulate the kinematics and trajectory planning. In Robotic System Toolbox it uses functional blocks to solve the Kinematics and Inverse Kinematics of PUMA560 robot. The Trajectory planning of robot is to plan the displacement, velocity and acceleration of each joint in the process of robot motion by a given path point. Selection of path points, interpolation of robot trajectory and processing of constrained optimization problems. It uses two motion trajectory planning: (PTP) point-to-point motion trajectory planning and (CP) continuous trajectory planning.

Z. M. Bi and Sherman Y. T. Lang [47] proposes the CAD and scanner based robotic coating system is proposed. Its software system consists of following things: data processing system, automatic programming and simulation system. Here data processing system is accomplished to generate the precise surface model from points-cloud or as CAD model designed in modelling software. The automatic program will allow to create robot program and simulation allows to validate the model. The methodology for generating robot program is shown in the Figure-2.15 (a), (b), (c) through tag points, path and trajectory on the surface.

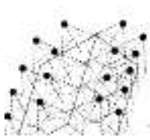


Figure- 2.20 (a) Tag points

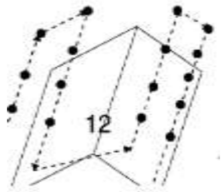


Figure-2.20 (b) Path

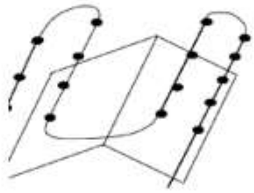


Figure-2.20 (c) Trajectory

Nairutya Patel, Riddhi Sarvaiya [48] proposed the material characteristics and material selection for the industrial robot for the application of spray-painting. It describes the material properties which strengthens the base of the manipulator. On the basis of required material properties, various aluminum grades are compared as shown in Table- 2.1.

Alloy	Formability or Workability	Weldability	Machining	Corrosion Resistance	Heat Treating	Strength	Typical Applications
Alloy 1100	Excellent	Excellent	Good	Excellent	No	Low	Metal Spinning
Alloy 2011	Good	Poor	Excellent	Poor	Yes	High	General Machining
Alloy 2024	Good	Poor	Fair	Poor	Yes	High	Aerospace Application
Alloy 3003	Excellent	Excellent	Good	Good	No	Medium	Chemical Equipment
Alloy 5052	Good	Good	Fair	Excellent	No	Medium	Marine Applications
Alloy 6061	Good	Good	Good	Excellent	Yes	Medium	Structural Applications
Alloy 6063	Good	Good	Fair	Good	Yes	Medium	Architectural Applications
Alloy 7075	Poor	Poor	Fair	Average	Yes	High	Aerospace Applications

Table-2.1 Material Properties of Various Aluminum grades

On the basis of comparison of material properties, it is concluded that the preferable material for better strength of arm is Aluminum alloy 7075. While the base is selected of the steel as material due to its high strength to per unit mass.

Chapter 3

Design of Manipulator

In this chapter, for the development of robotic manipulator design procedure is discussed; as many manipulators are available so-far but this manipulator is designed by keeping in mind that it will be mounted on the top of the structure climbing robot so that it should be robust, also it discusses CAD model for each part of the robotic manipulator, assembly of the manipulator, control system i.e., mode of actuation, sensors, camera spray gun and brief discussion about procedure for selection of the material.

3.1 Design Procedure

The design of the robotic manipulator plays an important role as the robotic manipulator is mounted on the top of climbing robot. The design procedure is iterative it includes some important considerations should be taken while designing the robot manipulator:

1. Development of the schemes: It is the first step of decide various parameters like structure, degree of freedom, workspace, link length, types of the joint, payload, type of the antenna.
2. Solid Modelling: After finalization of the scheme, each part of the manipulator is modelled and the assembly is prepared. The modelling is done using CAD software SOLIDWORKS 2020.

3. It should move with constant torque and friction created within the links should be neglected.
4. Masses of the robot should lump into the body itself which center of gravity should be gravity.
5. Stability of the joint is required at the very high distance so it is considered to be stable.

3.2 Degree of Freedom

The number of degrees of freedom a manipulator possesses is defined as the number of independent parameters required to fully specify its position and orientation in space. In robotics each joint acquires only one degree of freedom, so the degrees of freedom for manipulator are equal to number of joints. The Grobler and Kutzbach's equation for defining degree of freedom for manipulator is:

$$\text{dof} = m(N\text{-}1) - \sum_{i=1}^{j} C_i$$

where; m is 6 for spatial bodies

N is number of bodies including bodies = 5

j is number of the joints = 4 (three revolute joints and one prismatic joint)

C is independent joint constraints = 20

dof = 6(5-1) -20 = 24-20 =4.

Therefore; degrees of freedom of manipulator are four with three revolute joints and one prismatic joint. The base of the robot can revolve around its own axis, while second revolute joint can rotate at an angle θ_2 and third revolute joint can rotate at an angle θ_3 and prismatic joint can slide at distance d_4. So, it can easily get the required orientation of the robot. If the dof increases then there will be problem with the stability of the structure of the robot also cost increases.

3.3 Design of manipulator parts

The design of manipulator parts are as follows:

a) Base: The Base is an integral part which will be fixed on the structure climbing robot so it is designed accordingly. The diameter of the base is 200mm., as it would be mounted on the structure climbing robot whose dimension is 300*300mm as shown in the Figure-3.1 The design of the base should be such that it should revolve around its own axis. So, it is connected with revolute joint.

Figure-3.1 Base

b) Link 1: It is connected with base through revolute joint which will allow manipulator to get required position by revolving around the base as shown in the Figure- 3.2.

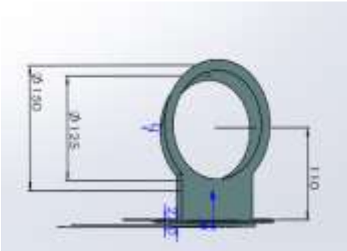


Figure- 3.2 Link 1

c) Link 2: It is shoulder linkage of the manipulator which is connected with revolute joint between Link 1 and Link 2with the help of revolute joint. The dimension of the Link2 is shown in the Figure-3.3. The structure of Link2 is designed in such a way that shoulder linkage is not bent due to the wind load and spray painting can be effectively fulfilled.

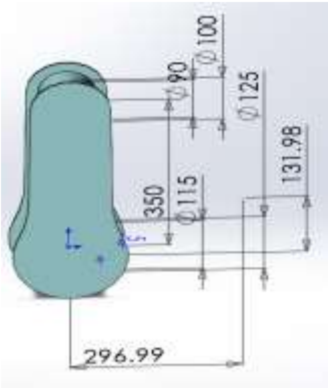


Figure- 3.3- Link2

d) Link 3: It is connected with Link 2 and Link 3 with the help of revolute joint and it will allow to get the orientation of the spray gun at required position. The Link3 is as shown in the Figure-3.4.

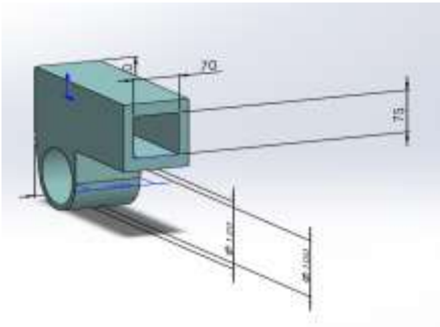


Figure-3.4. Link 3

e) Link 4: It will slide at the distance d4, this will allow to reach the required position of the gun as shown in Figure-3.5. The dimension of this link is 300mm.

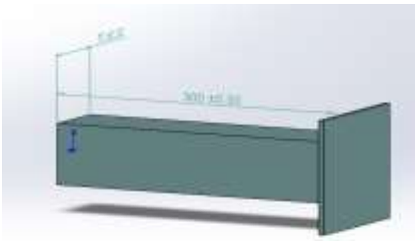


Figure-3.5 Link4

f) Clamping: The clamping will hold the gun for the spray-painting of antenna is shown in Figure-3.6.

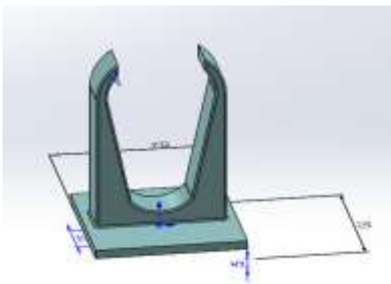


Figure-3.6 Clamping

The complete assembly of the robotic manipulator is as shown in the Figure-3.7 with the reference coordinate system joints and joint axis.

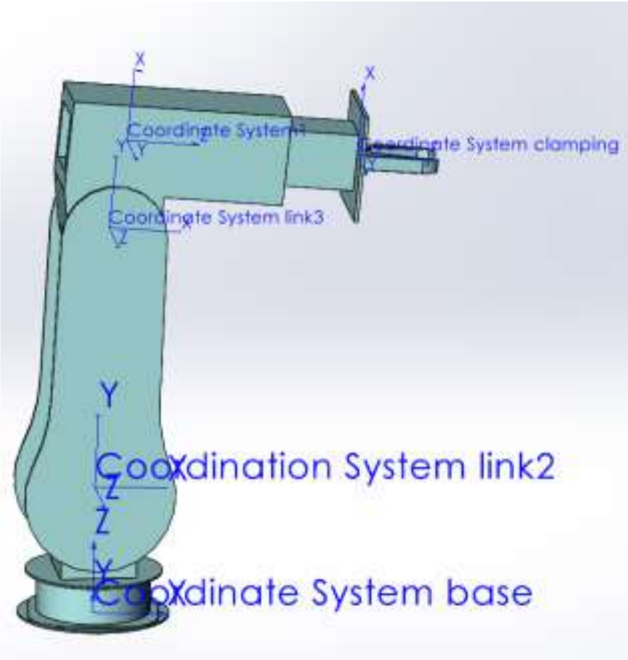


Figure-3.7 Assembly of the manipulator

3.4 Control System

The control system is an important part of the robotics system. There are two types of control system: open loop and closed loop system with and without feedback system respectively. It requires to build the mathematical model which calculates the joint variables and some sort of intelligence to perform the task. Apart from the mathematical model it requires devices which performs the actuation, intelligence which requires sensory capabilities and resources to send the signal of sensed variables to the person. The general block diagram for manipulator control system is shown in the Figure-3.8. Here in this section control system of the manipulator involves selection of actuation, sensors, vision system and method for spray painting which involves selection of spray-gun.

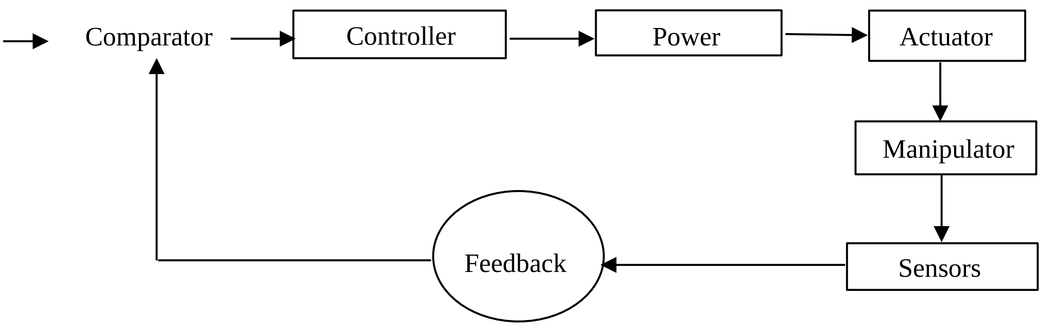


Figure- 3.8 General block diagram of Control System

3.4.1 Selection of Actuation

Selection of Actuator Actuators in robots are like strength in the human body. Without the actuators, the limbs of the robot cannot be in motion. There are many types of actuators existing like Pneumatic, Hydraulic, DC motors, Stepper motor and Servo motors but only Servo motors suit the needs of the project. Servos are selected because of their comparatively low cost and their simplicity of control. The main disadvantage of the servo motor is the loss of feedback position control to the external device providing the control pulse.

3.4.2 Selection of sensors and vision system

While task-planning and controlling of algorithm it requires the parameters which are characterizing the internal state of the manipulator and as well as the environment hence sensors are used in the manipulator for various types of functions. Here to detect the distance between the antenna and spray gun laser sensors are used as shown in Figure-3.8. Also, it requires to record the primarily targeted manipulation process of spray-painting as shown in Figure-3.9.

Figure- 3.9 Laser Sensors

Figure- 3.10 Vision system

3.4.3 Selection of spray-painting method and gun

Spraying is the technique of painting the surface with the appropriate thickness.
There are different techniques available for spraying currently it includes:

- Air-atomized
- Airless
- Electrostatic
- High-Volume Low Pressure
- Low-Volume High Pressure

The conventional method uses compressor, so compressed air allows to spray the fine atomized paint particles on the surface. There are two ways for spraying one is manual and other is automatic. In manual spraying the human triggers the gun for the spray purpose while the automatic spraying the trigger is functioned with the help of the PLC. In this project we are using the automatic airless spray gun for spraying purpose because the compressor cannot be carried along the structure climbing robot which will increase the complexity. The spray gun which is to be used is shown in Table- 3.1 with its specifications.

Specifications	Description
AOBEN Airless Electric Spray gun	
Type of Spray-painting technique	HVLP
Weight of Spray Gun	2kg
Capacity of container to fill paint	1000ml
Type of spray pattern	Circular, horizontal, vertical
Nozzle diameter	1.5,1.8,2.2,2.4 (mm)

Table- 3.1 Specifications of Spray gun

3.5 Selection of Material

The selection of material is an act of choosing the material which is best suited to achieve requirement of given application. The steps for material selection for manipulator:

1. Design requirement: The design requirement for the manipulator for spray painting includes: high repetition of motion, high labor intensity, light weight, working environment at high altitudes on the top of telecommunication antenna i.e., 100-200 feet.

2. Identification of material selection criteria: The properties for material selection criteria for manipulator includes:
    - ❖ Mass density — Sped of operation
    - ❖ Elasticity — Path of travel
    - ❖ Stiffness — Process variables
    - ❖ Tensile strength — Ductility
3. Material selection for present application:
   By comparing the material properties on the basis of the operating environment and other properties Table-3.2 is prepared.

No	Material	Mass Density (kgm^{-3})	Strength	Machining	Corrosion Resistance	Applications
1	Aluminium Alloy 7075	2810	High	Poor	Fair	Aerospace Application
2	Aluminium Alloy 6063	2700	Medium	Fair	Fair	Architectural Applications
3	Aluminium Alloy 6061	2700	Medium	Fair	Poor	Structural Applications
4	Plastic Alloy ABS	1020	Medium	Poor	Fair	Automobile and Building Materials
5	Plastic Acrylic	1200	Medium	Fair	Fair	Robotics, Automobile Sectors
No	Material	Mass Density (kgm^{-3})	Strength	Machining	Corrosion Resistance	Applications
6	Carbon Fibre-Hexcel	2000	Medium	Poor	Fair	Aerospace Applications

Table -3.2. Comparison on the basis of properties of various materials

The candidate material which is selected is: Acrylic (Medium-high impact) because it has very less mass density due to which manipulator is robust and can easily mounted on the base of structure climbing robot and its properties are shown in Table- 3.2:

Property	Value	Units
Mass Density	1200	Kg/m^3
Elastic Modulus	300 x 10^7	N/m^2
Tensile Strength	73 x 10^6	N/m^2
Yield Strength	45 x 10^6	N/m^2
Poisson's Ratio	0.35	NA
Shear Modulus	89 x 10^7	N/m^2

Table- 3.3 Material Properties

After applying Acrylic material to the assembly in solidworks we get mass properties of the whole assembly as shown in Figure-3.10.

Figure- 3.11 Mass properties of the manipulator

Chapter 4

Mathematical Modelling

In this chapter, mathematical modeling of four-degree of freedom manipulator is discussed which includes kinematic modeling i.e., forward kinematics and inverse kinematics modelling of the manipulator.

4.1 Kinematic Modelling

Kinematic model of four dof manipulator describes the position and orientation of the end-effector and relation between joint-link variables. The derivatives of kinematics deals with the mechanics of motion without considering the forces that cause it in order to follow the defined trajectory in the workspace. The problem of manipulator control requires both of direct and inverse kinematic models. The block diagram for both the model is shown in figure-4.1, wherein the commonality is the joint-link fixed parameters as well as joint- link variables parameters. The kinematic modelling is spitted into two problems as:

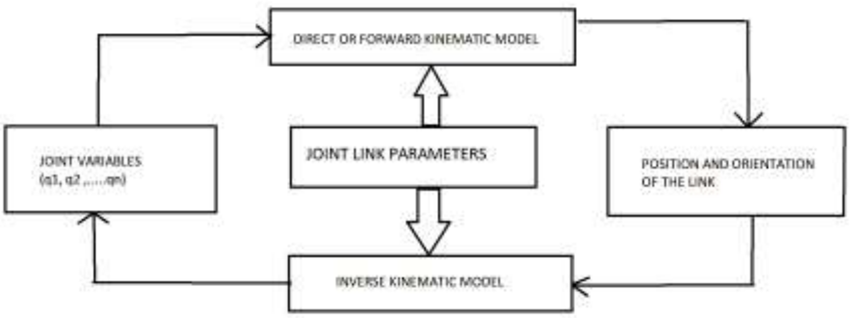


Figure- 4.1 The block diagram for direct and inverse kinematic model

4.1.1 Direct (or Forward) Kinematics

For the study of location placement of the manipulator analysis and verification of the D-H method is applied to 4-DOF manipulator. From mechanical structure of 4-DOF (RRRP) robot, there are three revolute joint and one prismatic joint in an open kinematic chain, continued proposed by Denavit and Hartenberg which is known as DH notation. The nomenclature used for in robotics while defining DH parameters are: two link parameters (a_i, α_i) and two joint parameters (d_i, θ_i).

- Link Length(a_i) – It is distance along x_i-axis from the point of intersection of xi axis and z_{i-1} axis to the origin of frame i.
- Link Twist(α_i) – It is the angle between z_{i-1} and z_i axes measured about x_i axis in the right-hand sense.
- Joint distance(d_i) – It is the distance measured along z_{i-1} axis from the origin of frame i-1 to the intersection of x_i axis with z_{i-1} axis.
- Joint angle(θ_i) – It is the angle between x_{i-1} and x_i axes measured about the z_{i-1} axis in the right-hand sense.

Denavit-Hartenberg algorithm **-** Link Frame Assignment allows to assign frames and determine the DH-parameters for each link of an n-DOF. It is divided into four steps:

- Step0: Identify and number the joints starting with the base and ending with end-effector. Number the link from 0 to n (base as 0).
- Step1: Align axis Z_i with axis of joint for joint (i+1) i = 0,1,2,3….
- Step2: The xi axis is fixed perpendicular to both z_{i-1} and z_i axes**.**
    - ❖ Case 1: If z_{i-1} and z_i intersects; choose intersection as origin and Xi axis will be perpendicular to plane containing zi-1 and zi axes. (a=0).
    - ❖ Case 2: If z_{i-1} and z_i parallel; joint i is revolute then X_i axis will be along that common normal which passes through origin of frame i+1 (d=0) and joint is prismatic then xi is arbitrarily chosen along the common normal and origin is placed at distal end of link i.
    - ❖ Case3: If z_{i-1} and z_i axis coincides; origin lies on the common axis; joint i is revolute origin is located to coincides with origin of frame i-1 and xi axis coincides with x_{i-1} axis (d=0) and joint i is prismatic x_i will be parallel to x_{i-1} axis (a=0) origin will be located at distal end of link i.
- Step3: Y-axis is fixed to complete right-hand orthogonal coordinate frame.

The tips for frame-assignment to manipulator:

- The joint frame should not need to coincide physically with the actual joint.
- It only needs to align with the axis of actuation
- The robot arm can be arranged in any configuration that suits the D-H parameters configuration that suits the D-H parameters.

With the help of algorithm Link Frame Assignment, the coordinate frame is assigned to each link, the joint-link parameters (a_i, α_i, d_i, θ_i) is shown in the Figure – 4.2.

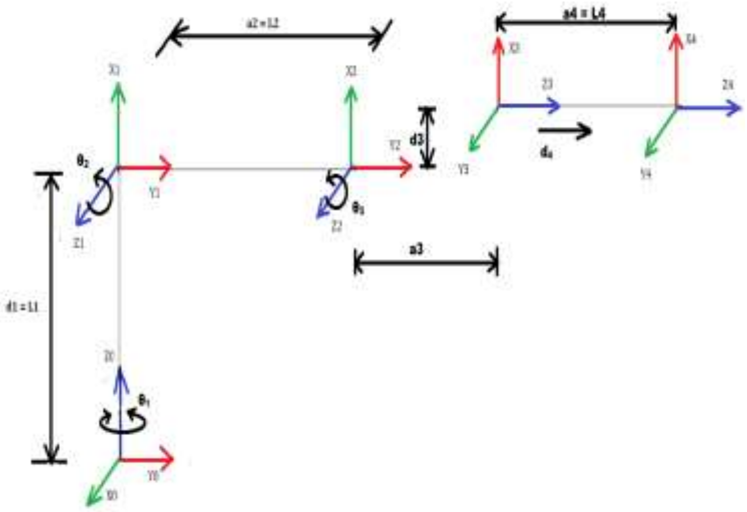


Figure- 4.2 Frame assignment for 4 dof manipulators

Axis	ai	αi	di	θi	Motion
1	0	90°	200	θ_1	Rotation of base
2	350	0	0	θ_2	Raises and lower (Upper arm)
3	118	180°	5	θ_3	Raises and lower (forearm)
4	0	0	d_4	0	Sliding motion

Table- 4.1 Joint Link parameter for 4 dof RRRP arm

The operations applied while transferring from frame i-1 to i;

Operation	Transformation

$T_{RZ}(\theta)$	Rotation about z_{i-1} axis by an angle θ_i
$T_z(d)$	Translation along z_{i-1} axis by distance d_i
$T_x(a)$	Translation by distance ai along xi axis
$T_x(\alpha)$	Rotation by angle αi about xi axis

Table- 4.2 Operations applied for Frame assignment

The link transformation matrices are:

${}^0T_1(\theta_1) = T_{RZ}(\theta_1)\, T_z(d_1)\, T_x(a_1)\, T_x(\alpha_1)$

$= T_{RZ}(\theta_1)\, T_z(200)\, T_x(0)\, T_x(90^\circ)$

$$= \begin{bmatrix} C_1 & S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.1$$

${}^1T_2(\theta_2) = T_{RZ}(\theta_2)\, T_z(d_2)\, T_x(a_2)\, T_x(\alpha_2)$

$= T_{RZ}(\theta_2)\, T_z(0)\, T_x(350)\, T_x(0^\circ)$

$$= \begin{bmatrix} C_2 & -S_2 & 0 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 350 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_2 & -S_2 & 0 & 350C_2 \\ S_2 & C_2 & 0 & 350S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.2$$

${}^2T_3(\theta_2) = T_{RZ}(\theta_3)\, T_z(d_3)\, T_x(a_3)\, T_x(\alpha_3)$

$= T_{RZ}(\theta_3)\, T_z(5)\, T_x(118)\, T_x(180^\circ)$

$$= \begin{bmatrix} C_3 & -S_3 & 0 & 0 \\ S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 118 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_3 & -S_3 & 0 & 118C_3 \\ S_3 & C_3 & 0 & 118S_3 \\ 0 & 1 & 5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.3$$

$^{3}T_4(d_4) = T_{RZ}(\theta_4)\ T_z(d_4)\ T_x(a_4)\ T_x(\alpha_4)$

$= T_{RZ}\ (0^{\circ})\ T_z\ (0)\ T_x(d_4)\ T_x\ (0^{\circ})$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 280 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 280 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.4$$

The overall transformation for the endpoint of the arm is:

$^{0}T_4 = {}^{0}T_1\ (\theta_1)\ {}^{1}T_2(\theta_2)\ {}^{2}T_3(\theta_2)\ {}^{3}T_4(d_4)$

$$\begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_2 & -S_2 & 0 & 350C_2 \\ S_2 & C_2 & 0 & 350S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_3 & -S_3 & 0 & 118C_3 \\ S_3 & C_3 & 0 & 118S_3 \\ 0 & 1 & 5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 280 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1S_{23} & -C_1c_{23} + S_1 & 5S_1 & 398C_1C_{23} + 350C_1C_2 \\ S_1S_{23} & S_1S_{23} - C_1 & 5C_1 & 398S_1C_{23} + 350C_1C_2 \\ S_{23} & C_{23} & 0 & 398S_{23} + 350S_2 + 200 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.5$$

Where $S_{23} = \sin(\theta_2 + \theta_3)$

$C_{23} = \cos(\theta_2 + \theta_3)$

$c_{23} = \cos(\theta_2 + \theta_3)$

4.1.2 Inverse Kinematics

For a given position and orientation of the end-effector, with respect to an immobile base or inertial reference frame, it is required to find a set of joint variables that would bring the end-effector i.e., clamping for spray gun in specified position and orientation. This is second problem and is referred to as the inverse kinematic model or inverse kinematics.

In other words, the inverse kinematic model is the determination of the joint displacements vector q ranges over the joint-space, as the set of positions and orientations of the clamping in Cartesian space. The robotic manipulator's transformation matrix T represents the orientation R and position D of the end effector with the respect to the base frame.

$$T = \begin{bmatrix} & R & & D \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

To find out the solutions of inverse kinematics problem there are two methods are available, one is closed form solutions and second one is numerical solutions. In the closed form solution, joint variables are resolve as open functions of the position and orientation of the clamping of the end effector while in numerical method uses iterative algorithm. Also, numerical methods are computationally exhaustive and very slower compared to the correct solution in singular and degenerate cases.

In the "closed form" in the present context means a solution where the method is based on solving the unknown of joint variables with the help of algebraic equations, trigonometric identities.

$$^{0}T_{4} = {}^{0}T_{1}\,{}^{1}T_{2}\,{}^{2}T_{3}\,{}^{3}T_{4} \qquad 3.6$$

The elements of the left-hand side of Eq. (3.6) are functions of the 4 joint displacement variables. While elements of the right-hand side matrix T are desired position and orientation of the clamping and are either zero or constant. As T matrix equality allows to implies elements by elements equality.

$$T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 3.7$$

Where, each r_{ij} has numeric value.

$$\begin{bmatrix} C_1S_{23} & -C_1c_{23}+S_1 & 5S_1 & 398C_1C_{23}+350C_1C_2 \\ S_1S_{23} & S_1S_{23}-C_1 & 5C_1 & 398S_1C_{23}+350C_1C_2 \\ S_{23} & C_{23} & 0 & 398S_{23}+350S_2+200 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$ 3.8

$S_1S_{23} = r_{21}$ 3.9

$C_1S_{23} = r_{11}$ 3.10

Dividing the Eq. (3.9) & Eq. (3.10) and we get;

$\tan(\theta_1) = \frac{r_{21}}{r_{11}}$

$\boldsymbol{\theta_1 = \text{Atan}\ (r_{11},\ r_{21})}$ 3.11

And then;

$S_{23} = r_{31}$ 3.12

$C_{23} = r_{32}$ 3.13

Dividing the Eq. (3.12) & Eq. (3.13) and we get;

$\tan(\theta_{2+}\ \theta_3) = \frac{r_{31}}{r_{32}}$

$\boldsymbol{\theta_{2+}\ \theta_3 = \text{Atan}\ (r_{32}, r_{31})}$ 3.14

And then;

$398C_1C_{23} + 350C_1C_2 = r_{14}$ 3.15

$398S_{23} + 350S_2 + 200 = r_{34}$ 3.16

Now, from Eq. (3.15)

Assume $X = r_{14} - 398C_1C_{23}$

$X = 350C_1C_2$ 3.17

Then; from Eq. (3.16)

Assume $Y = r_{34} - 398S_{23} - 200$

$Y = 350S_2$ 3.18

$5C_1 = r_{23}$ 3.19

Dividing the Eq. (3.17) and Eq. (3.18)

We get;

$\frac{Y}{X} = \frac{350S_2}{350C_1C_2}$

$\tan(\theta_2) = \frac{C_1 Y}{X}$

From the Eq. (3.19) substitute the value of C_1, we get

$$\boldsymbol{\theta_2 = \text{Atan}\left(\frac{-r_{23}Y}{5X}\right)} \quad 3.20$$

$$\boldsymbol{\theta_2 = \text{Atan}\,(5x, -r_{23}y)}$$

Now substitute the value of θ_2 in Eq. (3.14), we get

$$\boldsymbol{\theta_3 = \text{Atan}\,(r_{32}, r_{31}) - \theta_2} \quad 3.21$$

(As known that Atan 2(x, y) stands for the arctangent of y/x).

Thus, by performing inverse kinematics analysis model all the joint displacement variables are obtained.

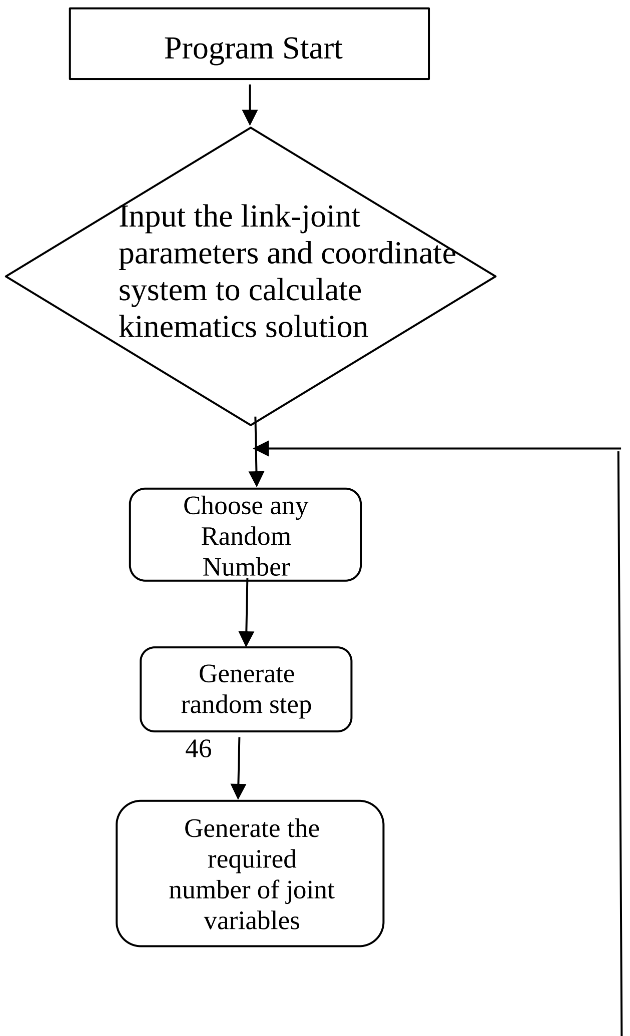
4.2 Workspace Analysis

The workspace analysis is defining the volume of space in which manipulator is able to locate its position of end-effector. Also, size and shape of the workspace analysis reproduces the work ability of the manipulator, which is very important for any application of the robot.

So, to obtain the workspace of manipulator; the range of the end effector obtained by the angles obtained by the joint displacement variables achieved in the space coordinate system.

Workspace Analysis is carried out with the help of Monte Carlo method. The basic idea of Monte Carlo method is: for solving the mathematical equations it requires to establish a probability model, by giving certain boundary conditions of random variables.

According to application procedure based on the Monte Carlo method, the algorithm flow chart is as shown in Figure- 4.3.



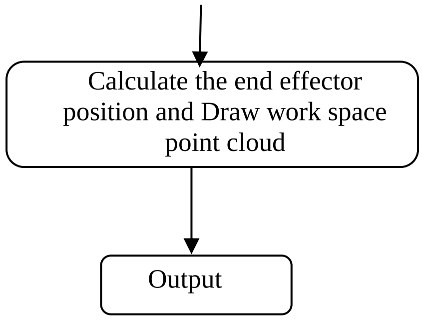


Figure-4.3 Algorithm for generation of workspace

After calculation of forward kinematics of the manipulator and containing the position vector of the manipulator end-point in the reference coordinate system according to the direct kinematics solution from the Equation- 3.5 is as below:

$X= d_4a_3\cos(\theta_1)\cos(\theta_2+\theta_3) + L2\cos(\theta_1)\cos(\theta_2);$
$Y = (d_4 + a_3)\sin(\theta_1)\cos(\theta_2+\theta_3) + L2\sin(\theta_1)\cos(\theta_2);$
$Z = (L_1+L_2)\sin(\theta_2) + d_4a_3\sin(\theta_2+\theta_3);$

While joint displacement variables are also given constraints:
$-90^\circ < \theta_1 < 180^\circ$,
$90^\circ < \theta_2 < 180^\circ$,
$90^\circ < \theta_2 < 180^\circ$,
$0 < d4 < 280;$

(All the values of revolute joints are in degrees while prismatic joint is in mm).

Here there after writing the code for workspace analysis in MATLAB and then obtaining the workspace as shown in Figure-4.4. From the workspace analysis dome like structure is obtained, length of reach is 750mm.

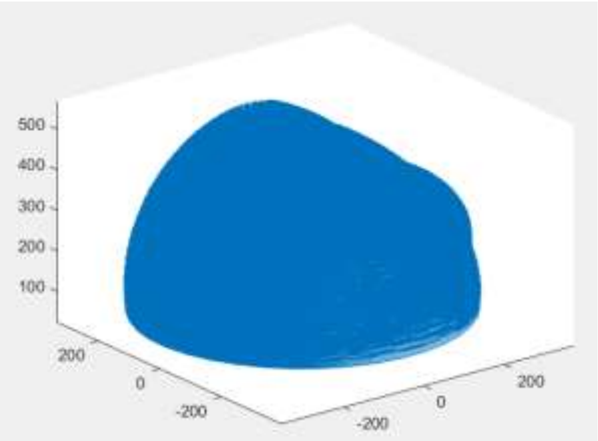


Figure- 4.4 Workspace Analysis of RRRP configuration

Chapter 5

Trajectory Planning

This chapter begins with describing the terminology involved in trajectory planning, steps to generate trajectory planning, generates a trajectory for spray painting of antenna, contains the rigidBodyTree model, trajectory model, inverse kinematics model code is generated in MATLAB.

The main objective of any trajectory planning algorithm is to achieve a smooth motion of the manipulator. The advantage of smooth motion is to reducing the vibrations and wear of the mechanical system. The aim of trajectory planning involves the requisite motion of the manipulator as function of time sequence; which are generated by interpolating the appropriate path through polynomial function.

The terminology used for trajectory planning are:

1. Path: It is locus of points where manipulator need0s to perform the specified task.
2. Trajectory: It is time history of position, velocity, acceleration at each position, velocity, acceleration of manipulator.
3. Knot Points: It is the set of intermediate points between the start and goal points on the trajectory.
4. Joint Space trajectory planning: In joint space trajectory each path points are detailed int terms of position and orientation of the end- effector with the relative to base frame. By application of inverse kinematics each point is converted into desired joint positions and smooth function is prepared for each joint.
5. Cartesian Space trajectory planning: In cartesian space trajectory planning, the path constraints (velocity, acceleration) are specified in cartesian coordinates and accordingly joint actuators are servoed in joint displacement variables.
6. Trajectory generation: It is defined as method of computing the trajectory as the function of time sequence in real time with the help of trajectory algorithm.

5.1 Steps in Trajectory Planning

For solving trajectory planning problem, it is divided into three steps:

1) Task Description: The first step in the motion planning is to identify the requirement of motion. This will become the requisite input for trajectory generation algorithm. The tasks can be grouped into three different categories:

   - Point- to- Point motion: In this motion, initial and final location of end-effector is specified such motion is used in pick and place operation. In PTP no particular specification about the intermediate location and planner is free to formulate any convenient path.
   - Continuous path motion: In this motion, with initial and final location of end-effector is specified along with particular path between them of end-effector in Cartesian space. In this motion user has to specify the type and parameters of the path to be tracked.
   - In third type of motion, more than two points of the path are specified. This type of motion is used where obstacles are available. The intermediate locations are the via points. Together they are referred to as path points.

2) Selecting and employing a trajectory planning technique: There are two categories of trajectory planning techniques:

   - Joint space technique: In PTP motion with or without via points, joint space techniques are employed where motion planning is completed on all the joint level as shown in Figure-5.1[]. This scheme is time-dependent function of all joint variables and their first two derivatives defines the desired motion of the manipulator.

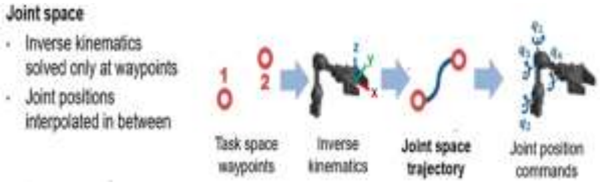


Figure- 5.1 Joint space technique

   - Cartesian space technique: For continuous path motion, cartesian space techniques are used. It provides time history of the location, velocity, and acceleration of end-effector with respect of base frame.

Using inverse kinematics, the corresponding joint displacement variables and their derivatives are calculated as shown in Figure- 5.2[].

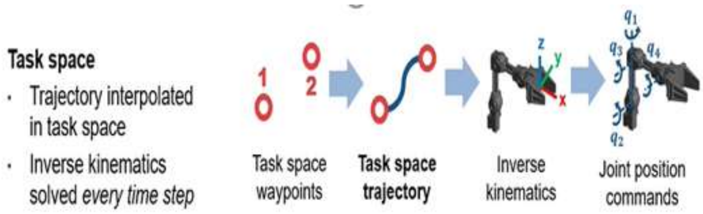


Figure-5.2 Cartesian space technique

3) Computing the trajectory: The last step is to calculate time-sequence values which are attained by functions generated from the trajectory planning technique.

5.2 B-spline Polynomial Trajectory

For defining any polynomial trajectory that connect the given 'k' waypoints; an approach is required where manipulator is needed to pass over all the waypoints without getting coming to rest at the intermediate points. For a path with 'k' path points, there are '(k-2)' intermediate waypoints and polynomial of '(k-1)' is required for connecting these 'k' path points in smooth way.

At individual path point in the cubic polynomial trajectory, it is required to get joint variables by inverse kinematics. Assume q_j as the value of joint variable q corresponding to way point j and any polynomial which is connecting waypoints j and (j+1) is function of time t which is denoted as $P_j(t)$ is as shown in Figure-5.3. It is defined in time interval of $t_{j-1} < t < t_j$. T_j denotes the travel time between the points j and j-1. The total time taken to travel the path is T with

$$T=\sum_{m-1}^{k-1} T_m \qquad 5.1$$

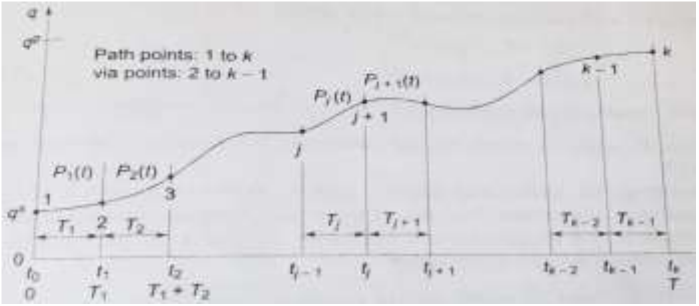


Figure- 5.3 Time interval for k path points and k-2 intermediate points

The joint position function, $q(t)$ for the entire path over interval 0 < t < T is defined by polynomial as:

$$
q(t) = \begin{cases} P_1(t) & T_0 < t < T_1 \\ P_2(t - T_1) & T_1 < t < T_2 \\ \vdots & \\ \vdots & \\ P_{k-1}\left(t - \sum_{m=0}^{k-2} T_m\right) & T_{k-2} < t < T_{k-1} \end{cases} \qquad 5.2
$$

For smooth trajectory at each intermediate point, additional constraints are required, by doing first derivative at each point we get joint velocities at each intermediate point and by doing second derivative we get joint acceleration at each intermediate points.

5.3 Methodology for Trajectory Generation

It adopts the offline programming methodology for generating trajectory for the spray-painting of an antenna in the structured environment as shown in Figure-5.1. The overview of SPRAYTOOL simulator and trajectory generation are:

- A description of the geometry of the part to be sprayed.
- A post-processed robot program.

For desired Integrated trajectory generation parameters such as the CAD model or surface model, characteristics of spray-gun model, paint distribution model, spray parameters are required. Ruled surface is considered as one of the fundamental parts in industrial surface modeling and it has wide applications because of its easiness to construct.

It is defined as polygon mesh which is created between two defined boundaries []. The objects are defined with the help of various shapes like line, circle, arc, points and other 2D-3D polylines. The surface created is a one-way mesh of straight lines which are drawn between the two boundaries.

The framework of the trajectory generation is developed as shown in the Figure-5.4. It uses the ruled surface which are created on the geometric surface of circular antenna which is considered as circular antenna of 300mm and with the help of appropriate diameter of the paint spot the model is prepared.

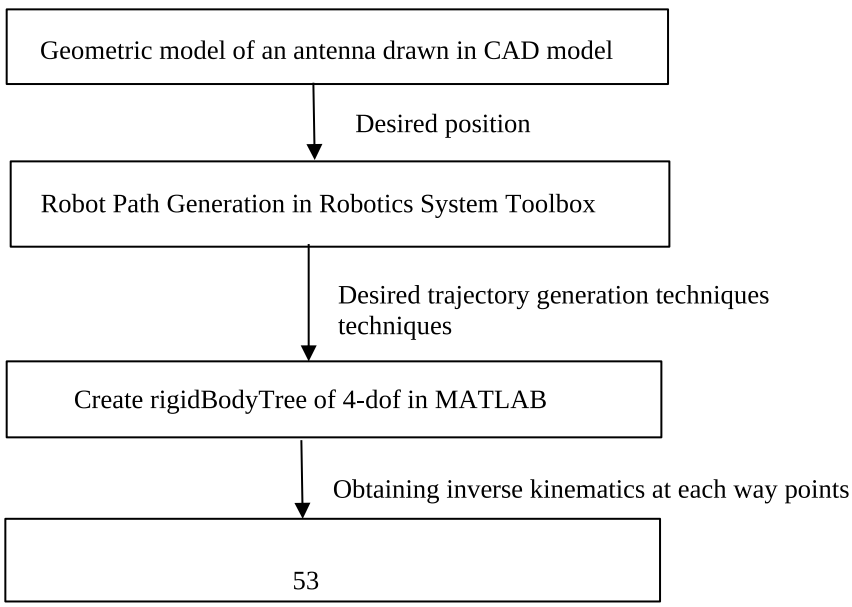


Figure- 5.4 Framework for obtaining Integrated Trajectory Generation

5.3.1 Geometric model

The Geometric model of a circular antenna of diameter of 300mm in Solidworks-2021. For obtaining the ruled surface of geometric model consider the input parameters for spray diameter, theoretical spray coverage, distance between the gun and surface by choosing the radius of full cone nozzle.

Mathematical relation is developed between spray coverage and angles.

$$TSC = 2L\tan\left(\frac{TSA}{2}\right) \qquad 5.3$$

where TSC- Theoretical Spray Coverage

ASC- Actual Spray Coverage

ASA- Actual Spray Angle

TSA- Theoretical Spray Angle

L- stand-off distance between the gun and surface.

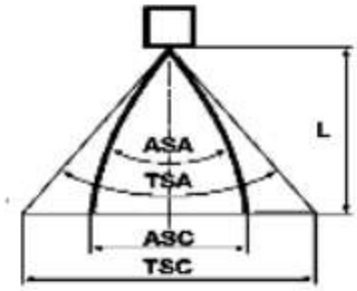


Figure-5.5 Theoretical Spray gun model

Therefore, taking input parameters as: Spray Angle-15°, L = 150mm, TSA = 35mm we got the geometric model as shown in Figure- 5.7 and desired waypoints in X-Y plane are obtained is as shown in Table-5.1

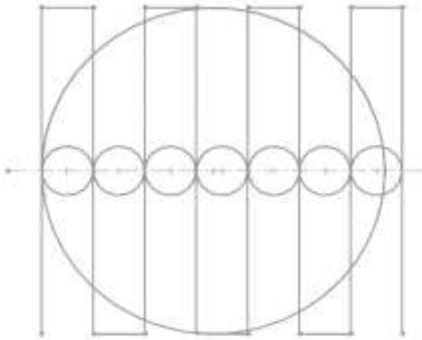


Figure-5.6 Geometric Model

No of way-points	1	2	3	4	5	6	7	8	9
X	-140	140	-105	-105	-70	-70	-35	-35	0
Y	150	-150	-150	150	150	-150	-150	150	150

Table-5.1(a) Waypoints

No of way-points	10	11	12	13	14	15	16	17	18
X	0	35	35	70	70	105	105	140	140
Y	-150	-150	150	150	-150	-150	150	150	-150

Table -5.1(b) Waypoints

5.3.2 Robot Path Generation

After generation of way-points the path is decided, the code is prepared with the help of Robotics System Toolbox in MATLAB. For generation of trajectory, it requires to prepare the path generation to follow the trajectory and output obtained is as shown in Figure-5.8 where all the way-points are traced.

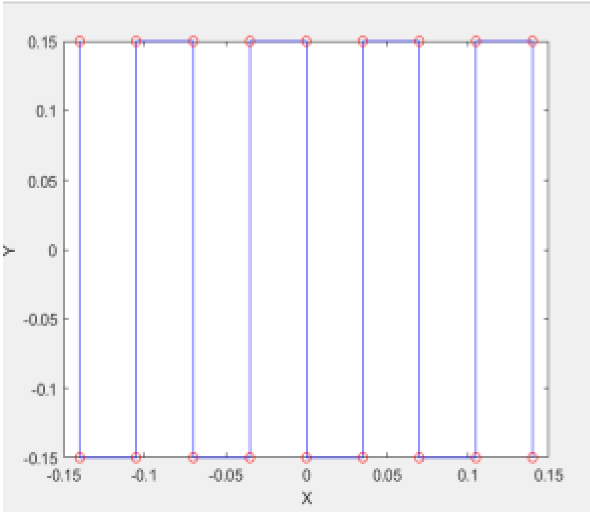


Figure-5.7 Waypoints plotted in MATLAB

5.3.3 Robot Trajectory Generation

For the Robot Trajectory Generation, it uses joint space technique. In this step trajectory is generated in Robotics System Toolbox with the help of waypoints plotted in the above step. It uses ‘bsplinepolytraj’ function for the robot trajectory generation. The output obtained is plotted is shown in the Figure-5.9.

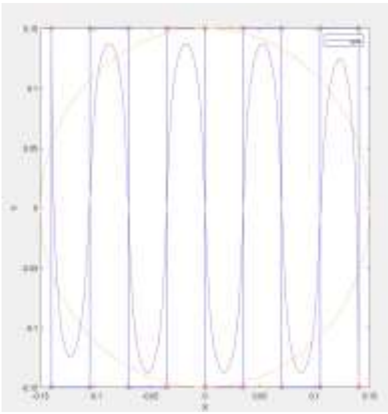


Figure-5.8 Trajectory Generation

The data obtained from the results of MATLAB describes 181 points are obtained. Now, further to obtain the joint displacement variables for the each obtained 181 points requirement of robot model arises.

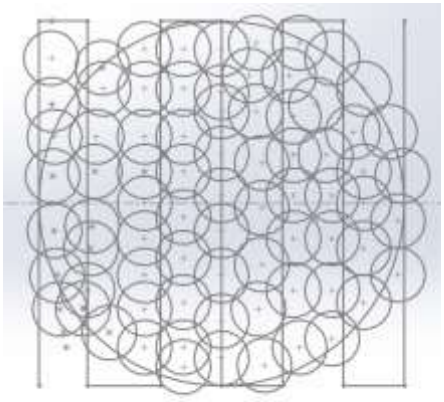


Figure-5.9 Paint patch at each point

The robot model known as rigidBodyTree in the Robotics System Toolbox is prepared in MATLAB by writing the code. In code detail description of each link-joint is described with the boundary constraints of joint displacement variables as the robotic manipulator drawn in CAD model. The output obtained is as shown in the Figure - 5.10. Further to obtain the joint displacement variables at each way-points generated with the help of inverse kinematics code which is generated in MATLAB is as shown in the Appendix.

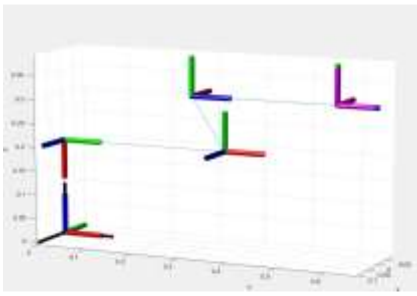


Figure- 5.10 rigidBodyTree Model

Chapter 6

Summary and Future Scope

6.1 Summary

- The criteria for the light weight manipulator are fulfilled which can be mounted on the structure climbing robot. Also, due to Airless spray-painting method it deducts the need to carry the compressor along with it.
- Through the Workspace Analysis of manipulator, it can cover the distance of 600mm which concludes that the it can also spray- paint the other antennas which are in the range of the workspace.
- With the help of offline programming method; generation of code for the trajectory concludes that coating of the antennas is fulfilled.

6.2 Future Scope

- To design the control system for the manipulating the robot.
- To prepare the protype of the manipulator.

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APPENDIX-A

The values obtained through the MATLAB code of joint angles at all waypoints are:

No	X	Y	Z	Q1	Q2	Q3	Q4

1	-0.14	0.15	0	43.02507	-61.1781	29.73859	-0.25452
2	-0.13965	0.081105	0	59.86356	-66.3424	30.39304	-0.28372
3	-0.13866	0.023843	0	80.26324	-69.1705	31.00175	-0.29577
4	-0.13713	-0.02266	0	99.40131	-69.4241	31.05006	-0.29675
5	-0.13514	-0.05926	0	113.6983	-68.2403	30.69547	-0.2921
6	-0.13278	-0.08683	0	123.1692	-66.7608	30.28577	-0.28576
7	-0.13016	-0.10625	0	129.2294	-65.5521	29.98504	-0.2801
8	-0.12735	-0.11837	0	132.9255	-64.8343	29.8239	-0.27651
9	-0.12444	-0.12407	0	134.9308	-64.6054	29.77594	-0.27533
10	-0.12154	-0.12422	0	135.6296	-64.8472	29.82547	-0.27658
11	-0.11873	-0.11968	0	135.2403	-65.492	29.96099	-0.27981
12	-0.1161	-0.11131	0	133.7908	-66.4838	30.18333	-0.28453
13	-0.11375	-0.1	0	131.3319	-67.7311	30.48928	-0.29002
14	-0.11174	-0.08652	0	127.7541	-69.125	30.86733	-0.29565
15	-0.11004	-0.0713	0	122.9506	-70.5765	31.30185	-0.30097
16	-0.1086	-0.05469	0	116.7336	-71.9722	31.75915	-0.30561
17	-0.10738	-0.03704	0	109.0092	-73.1812	32.18677	-0.30928
18	-0.10631	-0.01869	0	99.97724	-74.0532	32.51393	-0.31173
19	-0.10536	1.39E-17	0	90.00001	-74.4475	32.66714	-0.31278
20	-0.10448	0.018692	0	79.85447	-74.3296	32.61902	-0.31247
21	-0.1036	0.037037	0	70.34618	-73.7352	32.38265	-0.31085
22	-0.10268	0.054688	0	61.95939	-72.7694	32.00953	-0.30807
23	-0.10166	0.071296	0	54.96641	-71.6012	31.57889	-0.30444
24	-0.10051	0.086516	0	49.28155	-70.3817	31.15597	-0.30032
25	-0.09917	0.1	0	44.7699	-69.2137	30.77813	-0.29604
26	-0.09759	0.111458	0	41.19684	-68.2039	30.47467	-0.29206
27	-0.09582	0.120833	0	38.41605	-67.3964	30.24837	-0.28868
28	-0.09388	0.128125	0	36.24221	-66.7813	30.08612	-0.28598
29	-0.09182	0.133333	0	34.55411	-66.3873	29.9872	-0.28419
30	-0.08968	0.136458	0	33.31064	-66.1956	29.94064	-0.2833
31	-0.0875	0.1375	0	32.4712	-66.2414	29.95158	-0.28352
32	-0.08532	0.136458	0	32.00161	-66.5033	30.01443	-0.28472
33	-0.08318	0.133333	0	31.9706	-67.0056	30.13776	-0.28698
34	-0.08112	0.128125	0	32.33786	-67.7434	30.32678	-0.29017
35	-0.07918	0.120833	0	33.25001	-68.7243	30.59322	-0.29417
36	-0.07741	0.111458	0	34.76723	-69.9518	30.9516	-0.29881
37	-0.07583	0.1	0	37.16212	-71.4425	31.42389	-0.30396
38	-0.07449	0.086516	0	40.73738	-73.1464	32.01374	-0.30923
39	-0.07335	0.071296	0	45.79241	-74.9997	32.71535	-0.31426
40	-0.07237	0.054687	0	52.92803	-76.8505	33.47787	-0.31863
41	-0.07151	0.037037	0	62.63919	-78.5404	34.22711	-0.32206
42	-0.07074	0.018692	0	75.18461	-79.783	34.81061	-0.32428
43	-0.07	-2.78E-17	0	89.99996	-80.3167	35.06941	-0.32515

44	-0.06926	-0.01869	0	105.1011	-80.0152	34.91725	-0.32466
45	-0.06849	-0.03704	0	118.3755	-78.9942	34.41293	-0.32291
46	-0.06763	-0.05469	0	128.9788	-77.4928	33.69602	-0.32001
47	-0.06665	-0.0713	0	136.9091	-75.7749	32.9176	-0.3162
48	-0.06551	-0.08652	0	142.866	-74.0733	32.19646	-0.31188
49	-0.06417	-0.1	0	147.2995	-72.5001	31.57741	-0.30738
50	-0.06259	-0.11146	0	150.6886	-71.1611	31.08949	-0.30313
51	-0.06082	-0.12083	0	153.2834	-70.0957	30.72841	-0.29945
52	-0.05888	-0.12813	0	155.3072	-69.2802	30.46896	-0.29645
53	-0.05682	-0.13333	0	156.9208	-68.7353	30.30439	-0.29435
54	-0.05468	-0.13646	0	158.1624	-68.4375	30.21768	-0.29318
55	-0.0525	-0.1375	0	159.1022	-68.4196	30.21258	-0.2931
56	-0.05032	-0.13646	0	159.7712	-68.6558	30.27988	-0.29404
57	-0.04818	-0.13333	0	160.1205	-69.176	30.43066	-0.29606
58	-0.04612	-0.12813	0	160.2075	-69.9714	30.6697	-0.29901
59	-0.04418	-0.12083	0	159.9027	-71.0614	31.01483	-0.30281
60	-0.04241	-0.11146	0	159.1798	-72.4547	31.48623	-0.30727
61	-0.04083	-0.1	0	157.8046	-74.1913	32.12095	-0.31224
62	-0.03949	-0.08652	0	155.4563	-76.2465	32.93934	-0.31736
63	-0.03835	-0.0713	0	151.7568	-78.58	33.95503	-0.32222
64	-0.03737	-0.05469	0	145.6385	-81.0822	35.14319	-0.3264
65	-0.03651	-0.03704	0	135.3899	-83.5982	36.43607	-0.32959
66	-0.03574	-0.01869	0	117.6461	-85.7102	37.59318	-0.33152
67	-0.035	9.71E-17	0	90.00019	-86.6872	38.14734	-0.33219
68	-0.03426	0.018692	0	61.40138	-85.9436	37.7088	-0.3317
69	-0.03349	0.037037	0	42.15795	-83.9942	36.58534	-0.33002
70	-0.03263	0.054688	0	30.79406	-81.5884	35.25731	-0.32716
71	-0.03165	0.071296	0	23.96997	-79.1554	33.99711	-0.32334
72	-0.03051	0.086516	0	19.42274	-76.9048	32.91674	-0.31892
73	-0.02917	0.1	0	16.27782	-74.9181	32.03744	-0.31426
74	-0.02759	0.111458	0	13.90317	-73.2612	31.36172	-0.3098
75	-0.02582	0.120833	0	12.05589	-71.9526	30.86747	-0.30588
76	-0.02388	0.128125	0	10.56834	-70.9491	30.51292	-0.30263
77	-0.02182	0.133333	0	9.287984	-70.2568	30.28158	-0.30025
78	-0.01968	0.136458	0	8.212359	-69.8479	30.15041	-0.29879
79	-0.0175	0.1375	0	7.253197	-69.7484	30.1193	-0.29843
80	-0.01532	0.136458	0	6.395472	-69.9282	30.17521	-0.29908
81	-0.01318	0.133333	0	5.655267	-70.42	30.32998	-0.30082
82	-0.01112	0.128125	0	4.952374	-71.208	30.58564	-0.3035
83	-0.00918	0.120833	0	4.355186	-72.3203	30.96382	-0.30704
84	-0.00741	0.111458	0	3.797037	-73.7646	31.48586	-0.31124
85	-0.00583	0.1	0	3.319444	-75.5965	32.19791	-0.31598
86	-0.00449	0.086516	0	2.978047	-77.8128	33.13337	-0.32087

87	-0.00335	0.071296	0	2.650001	-80.3938	34.32209	-0.3255
88	-0.00237	0.054687	0	2.512337	-83.3109	35.78843	-0.32943
89	-0.00151	0.037037	0	2.321704	-86.5354	37.55036	-0.33228
90	-0.00074	0.018692	0	2.144536	-89.9952	39.58983	-0.33368
91	1.73E-18	0	0	2.144536	-93.6757	41.90377	-0.33338
92	0.000736	-0.01869	0	2.144166	-97.5292	44.45127	-0.3312
93	0.001512	-0.03704	0	2.321336	-101.511	47.16944	-0.32703
94	0.00237	-0.05469	0	2.512202	-105.622	50.00251	-0.32082
95	0.003349	-0.0713	0	2.649894	-109.79	52.81815	-0.31274
96	0.00449	-0.08652	0	2.978005	-113.968	55.48308	-0.3031
97	0.005833	-0.1	0	3.319433	-118.053	57.83209	-0.2925
98	0.007406	-0.11146	0	3.79702	-121.867	59.70956	-0.28188
99	0.009182	-0.12083	0	4.355178	-125.187	61.04286	-0.27231
100	0.01112	-0.12813	0	4.952367	-127.926	61.91216	-0.26433
101	0.013179	-0.13333	0	5.655262	-129.949	62.4137	-0.25844
102	0.015319	-0.13646	0	6.395468	-131.24	62.66963	-0.2547
103	0.0175	-0.1375	0	7.253193	-131.717	62.74985	-0.25333
104	0.019681	-0.13646	0	8.212354	-131.452	62.70794	-0.25409
105	0.021821	-0.13333	0	9.287977	-130.368	62.52683	-0.25718
106	0.02388	-0.12813	0	10.56833	-128.554	62.1716	-0.26235
107	0.025818	-0.12083	0	12.05588	-125.989	61.54616	-0.26962
108	0.027594	-0.11146	0	13.90316	-122.801	60.55071	-0.27856
109	0.029167	-0.1	0	16.27778	-119.066	59.06892	-0.28879
110	0.03051	-0.08652	0	19.42268	-115.052	57.10132	-0.29926
111	0.031651	-0.0713	0	23.96992	-111.051	54.79295	-0.30882
112	0.03263	-0.05469	0	30.79399	-107.246	52.3455	-0.3168
113	0.033488	-0.03704	0	42.15777	-103.888	50.04935	-0.32272
114	0.034264	-0.01869	0	61.40111	-101.399	48.30185	-0.32635
115	0.035	-3.33E-16	0	89.9998	-100.496	47.66253	-0.32749
116	0.035736	0.018692	0	117.6459	-101.677	48.49653	-0.32598
117	0.036512	0.037037	0	135.3897	-104.368	50.399	-0.32194
118	0.03737	0.054687	0	145.6384	-107.863	52.84798	-0.31551
119	0.038349	0.071296	0	151.7568	-111.748	55.47716	-0.30696
120	0.03949	0.086516	0	155.4563	-115.872	58.06411	-0.29655
121	0.040833	0.1	0	157.8045	-120.04	60.35287	-0.28498
122	0.042406	0.111458	0	159.1797	-124.037	62.14725	-0.27332
123	0.044182	0.120833	0	159.9027	-127.567	63.35442	-0.26284
124	0.04612	0.128125	0	160.2075	-130.496	64.07467	-0.25418
125	0.048179	0.133333	0	160.1205	-132.698	64.44783	-0.24773
126	0.050319	0.136458	0	159.7713	-134.155	64.61638	-0.24351
127	0.0525	0.1375	0	159.1022	-134.819	64.67123	-0.2416
128	0.054681	0.136458	0	158.1624	-134.769	64.66777	-0.24175
129	0.056821	0.133333	0	156.9208	-133.929	64.60739	-0.24414

130	0.05888	0.128125	0	155.3072	-132.393	64.46417	-0.24851
131	0.060818	0.120833	0	153.2834	-130.11	64.16117	-0.25503
132	0.062594	0.111458	0	150.6886	-127.184	63.59601	-0.2634
133	0.064167	0.1	0	147.2995	-123.667	62.63103	-0.27346
134	0.06551	0.086516	0	142.8661	-119.851	61.20403	-0.28425
135	0.066651	0.071296	0	136.9092	-116.155	59.43598	-0.29436
136	0.06763	0.054687	0	128.9788	-112.846	57.55429	-0.30288
137	0.068488	0.037037	0	118.3755	-110.25	55.90711	-0.30907
138	0.069264	0.018692	0	105.1011	-108.616	54.80703	-0.31269
139	0.07	-1.67E-16	0	90.00004	-108.151	54.4864	-0.31368
140	0.070736	-0.01869	0	75.18471	-108.968	55.05847	-0.31192
141	0.071512	-0.03704	0	62.63926	-110.959	56.42958	-0.30737
142	0.07237	-0.05469	0	52.92806	-113.897	58.37115	-0.30003
143	0.073349	-0.0713	0	45.79243	-117.501	60.55867	-0.29019
144	0.07449	-0.08652	0	40.7374	-121.619	62.70602	-0.27816
145	0.075833	-0.1	0	37.16213	-125.917	64.45194	-0.26518
146	0.077406	-0.11146	0	34.76724	-130.039	65.60333	-0.25272
147	0.079182	-0.12083	0	33.25002	-133.592	66.18199	-0.24217
148	0.08112	-0.12813	0	32.33787	-136.462	66.3884	-0.23383
149	0.083179	-0.13333	0	31.9706	-138.61	66.40264	-0.22769
150	0.085319	-0.13646	0	32.00161	-140.058	66.34879	-0.22359
151	0.0875	-0.1375	0	32.47119	-140.807	66.30072	-0.22148
152	0.089681	-0.13646	0	33.31063	-140.938	66.29066	-0.22112
153	0.091821	-0.13333	0	34.5541	-140.39	66.3335	-0.22265
154	0.09388	-0.12813	0	36.2422	-139.256	66.40965	-0.22581
155	0.095818	-0.12083	0	38.41605	-137.467	66.48895	-0.2308
156	0.097594	-0.11146	0	41.19683	-135.087	66.50475	-0.23746
157	0.099167	-0.1	0	44.7699	-132.084	66.36059	-0.24594
158	0.100512	-0.08652	0	49.28153	-128.626	65.93184	-0.25585
159	0.101665	-0.0713	0	54.9664	-125.13	65.16346	-0.26603
160	0.102676	-0.05469	0	61.95935	-121.983	64.14575	-0.27526
161	0.103596	-0.03704	0	70.34617	-119.576	63.14028	-0.2823
162	0.104475	-0.01869	0	79.85444	-118.191	62.4668	-0.28631
163	0.105365	-1.53E-16	0	89.99999	-117.923	62.33077	-0.28708
164	0.106315	0.018692	0	99.97722	-118.81	62.80515	-0.28449
165	0.107377	0.037037	0	109.0092	-120.867	63.8376	-0.27835
166	0.1086	0.054687	0	116.7336	-123.952	65.17625	-0.26895
167	0.110037	0.071296	0	122.9506	-127.837	66.46549	-0.25702
168	0.111736	0.086516	0	127.754	-132.139	67.36389	-0.24399
169	0.11375	0.1	0	131.3319	-136.357	67.73146	-0.23157
170	0.116105	0.111314	0	133.7908	-140.08	67.67961	-0.22092
171	0.118733	0.119676	0	135.2403	-142.963	67.42501	-0.2128
172	0.121543	0.124219	0	135.6296	-144.792	67.17411	-0.20768

173	0.124444	0.124074	0	134.9308	-145.469	67.06294	-0.2058
174	0.127346	0.118374	0	132.9255	-144.829	67.17356	-0.20757
175	0.130156	0.10625	0	129.2294	-142.791	67.50382	-0.21317
176	0.132784	0.086834	0	123.1692	-139.25	67.96126	-0.2228
177	0.135139	0.059259	0	113.6983	-134.736	68.27401	-0.23512
178	0.137129	0.022656	0	99.40132	-131.016	68.26414	-0.24543
179	0.138663	-0.02384	0	80.26325	-131.772	68.47978	-0.24298
180	0.139651	-0.08111	0	59.86356	-140.441	68.83204	-0.21757
181	0.14	-0.15	0	43.02507	-154.867	66.68153	-0.17514