KINEMATIC MODELLING AND SIMULATION OF 3-AXIS ROBOTIC ARM FOR PERFORMING WELDING OPERATIONS WITH ARBITRARY WELD JOINT PROFILES

A thesis submitted in fulfillment of the requirements for the degree of

Master's degree

in

Industrial Design

by

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MAY, 2015

Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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CERTIFICATE

This is to certify that the thesis entitled "***Kinematic Modelling and Simulation of 3-Axis Robotic Arm for Performing Welding Operations with Arbitrary Weld Joint Profiles"*** being submitted by ***Chukka Atchuta Rao***, Roll No. **213ID1358,** to the National Institute of Technology, Rourkela for the award of ***Master's degree*** in Industrial Design, is a bona fide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

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In my opinion, the thesis is of the standard required for the award of Master's degree in Industrial Design.

To the best of my knowledge, he bears a good moral character and decent behavior.

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Abstract

Robot welding is a fast and accurate welding to obtain a good joint strength. In this thesis, a 3-axis robotic arm has been modeled using CAD tool for performing welding operations. For the developed robotic arm, forward & inverse kinematic analyses have been performed to move the weld torch in the desired trajectory. A new seam tracking methodology, named sewing technique has been introduced for the welded joints available in Computer Aided Design (CAD) environment. This methodology, gives the seam path by drawing a line through the adjacent centroids of curve fitted in the weld joint volume. Obtained geometric path and kinematic constraints are given as input to the modeled robot for performing welding operation followed by desired trajectory. Validation of the developed methodology has been done through simulation results while performing welding operations for different weld profiles.

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NOMENCLATURE

CAD	Computer Aided Design
UAV	Unnamed Aerial Vehicle
AUV	Autonomous Underwater Vehicle
AGVs	Automatic Guided Vehicles
B	Local frame
${}^{B}r_{p}$	Point P representation in local frame B
DOF	Degrees of Freedom
D-H	Denavit- Hartenberg
GMAW	Gas Metal Arc Welding
$(robotx, roboty)$	Point represented of robot
i_X, j_Y, k_Z	Unit vectors along the coordinate axes OXYZ
i_x, j_y, k_z	Unit vectors along the coordinate axes oxyz
p	position vector
α_i	Rotation about the X-axis
θ_i	Rotation about the Z-axis
X	x co-ordinate value
Y	y co-ordinate value
Z	z co-ordinate value

Chapter 1

INTRODUCTION

Origin of the Work

Problem Statement

Objectives

Thesis Overview

1. INTRODUCTION

With an unremitting requirement for better productivity and the provision of end products having uniform quality, manufacturing industries are turnoff more and more toward the computer-based automation. Now a days, industries are having automated machines are used to perform variety of prearranged tasks in manufacturing process. Nevertheless automated machines are generally expensive as well as inflexible in performing variety of tasks. Due to these limitations, the development of robots having capable of performing a variety of manufacturing functions in a more flexible working environment at lower production costs.

Robotics is the branch of electrical engineering, mechanical engineering, control engineering and software engineering that deals with the design, development, operation, and utilization of robots using computer systems for their control, bidirectional communication and information -processing. Motion planning of the robot that is kinematics and dynamics part is taken care by control and mechanical aspect of robotics while electrical aspect of robotics deals with powering the on board sensors and actuators module. Use of artificial intelligence technique through programming and implementation of suitable algorithm makes the robot intelligent and autonomous.

Robotics is a multidisciplinary branch and it finds numerous applications in various fields. The multidisciplinary view of robotics is shown below in the figure 1.1.

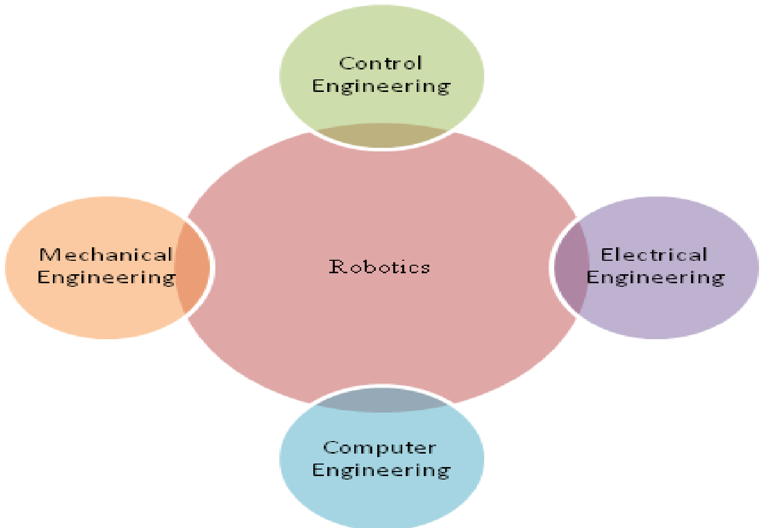


Fig.1.1 Multifaceted view of Robotics

Hence there are different types of robots and can be classified depending on their application, movement etc.

Depending on application and field of use robots can be classified as:

- Industrial robots: These are the robots utilized as a part of a modern assembling environment. Normally these are mechanized arms particularly produced for applications like welding, material taking care of, painting and others. Some of the examples of industrial robots are SCARA robots, delta robots and Cartesian co-ordinate robots etc.
- Medical robots: Robots used in various medical applications such as high precision surgical robots, rehabilitation robots, bio-robots and telepresence robots etc.
- Domestic robots: Robots used in household applications like robotic vacuum cleaners, robotic pool cleaners, floor washing robots etc.
- Military robots: Robots used in defense sector and military applications like bomb detection robotic vehicle, Unmanned Aerial Vehicle (UAV), Autonomous Underwater vehicle (AUV), reconnaissance drone etc.
- Space robots: These are special types of robots used in space shuttles, international space station etc. Mars exploration rovers of NASA like curiosity, opportunity and sojourner are few examples of space robots.
- Entertainment robots: There are some robots used for entertainment purpose like Gupi (a robotic Pig), Aibo (robotic dog) etc.

There is another way of classification of robots based on their movement and kinematics such as:

- Stationary robots: Robots which are fixed at a particular position like industrial robots and manipulators.
- Mobile robots: Robots having ability to move around their surroundings and not altered to physical area. Automatic Guided Vehicles (AGVs) are examples of mobile robot. Mobile robots can be classified as two types such as:
    a. Legged robots: Robots having legs as actuators for their movement and locomotion.
    b. Wheeled robots: Robots with wheels attached to motors and the motors are controlled by the user through programming.

Advancement of technology made conceivable robots utilized in distinctive conditions like area, water and air. Some of the examples of it are Automatic Ground Vehicle (AGV), Unmanned Aerial Vehicle (UAV) and Autonomous Underwater Vehicle (AUV).

Classification of robots can also be done based on their method of control like

- Autonomous robots: These are the robots which work on their own without control of any external agent like human operator. This task is achieved through programming and implementation of suitable algorithm.
- Semi-autonomous robots: In case of autonomous robot all the desired tasks are performed by the robot itself and there is no need of external control. But a semi-automated robot performs some task continuously on its own while few things are performed by the operator remotely through some mechanism. The best example is pipeline inspection robot.
- Manually controlled robots: Robots controlled by human operator through connecting wire or by remote from a distant location.

Application of robotics is enormous which spans from agriculture to space explorations. Various fields of application of robotics include healthcare, research, agriculture, entertainment, space exploration, defense, search & rescue and radioactive material handling etc.

1.1 Origin of the Work

Most of the construction machinery parts are welded structures and arc welding technique is mainly used to produce such products. The welding process has been automated from the last few decades through the use of robots and 90% or more of total weld lines are currently automated.

The past research work concerned primarily on weld geometry/seam tracking or relation among very few process related parameters. But these involve more complications while performing welding operations. The proposed system is a simple seam tracker can be used for continuous and long seam welding. It can be controlled and monitored remotely without human operation, thereby reducing the risk of hazards. Since the welding operation can be monitored initially in the CAD environment, the produced weldments would be uniform, superior and the cycle time can be faster in comparison to the presently available systems.

1.2 Problem Statement

The new method is based on sewing technique and simulation in CAD environment. In this approach, a manipulator has been modelled in CAD to perform require welding task.

Manipulator kinematics has been performed to get required positions of the weld tool and joint angles by using inverse kinematics. The development of CAD assisted robot welding covers mechanical design, Extraction of coordinate data, inverse kinematic solution, and simulation of the robot foe arbitrary welding profiles.

1.3. Objectives

The aim of the research work is to introduce the new methodology for robot welding in CAD environment to increase productivity in manufacturing industries. The objective of the current study is to design and perform the robot welding in CAD environment as well as validation of simulation results.

The following objectives were consequently stated for this research work:

- To perform forward and inverse kinematic analysis of a 3-axis robot.
- To extract the coordinate data from the CAD geometry of existed welded joints.
- To obtain weld seam from sewing technique.
- To simulate the robot to follow the weld seam path obtained from seam tracker.
- To validate simulation results of robot with help of CATIA.

1.4. Thesis Overview

This dissertation is organized as follows

- *Chapter 2* describes the back ground of development of robot welding by using CAD model. This includes the literature survey on kinematic analysis of robotic arm, welding, and robotic welding.
- *Chapter 3* addresses mechanical design and architecture of the robot arm. This includes rotation kinematics with respect to the different axis. The arm equation for forward kinematic analysis has to model for finding the position of the end-effector for a given link parameters and angles of joints. Inverse kinematic model has to develop for a given position of the end-effector and link parameters.
- *Chapter 4* outlines methodology for CAD assisted robot welding. Robot arm has to be modeled and point co-ordinate data has to be extracted from the CAD geometry. An inverse kinematic solution has to be prepared for simulation of welding operation.
- *Chapter 5* devotes the experimental analysis and it includes a program for inverse kinematic solution, simulation of robot welding, and validation of simulation.
- *Chapter 6* addresses the conclusions and future scope.

Chapter 2

LITERATURE SURVEY

Manipulator Kinematics

Welding

Robot Welding

Summary

2. LITERATURE SURVEY

A manipulator in this study is mounted on the fixed base and three links are placed one on another. The end effector carries the weld tool to perform welding operation in necessary position. Kinematic analysis includes forward and inverse kinematics has been performed to obtain the position of the end effector and joint angles. A wide literature has been studied and analysed on the manipulator kinematics.

2.1. Manipulator Kinematics

Merlet [1] described about optimal parallel manipulators and they designed a new method for manipulators by considering the constraints like work space, and geometry. Wen and Yii [2] explained about the kinematic chains with joints synthesis and they developed a straight forward approach for the computer aided structural synthesis. Based on the planned algorithm, a computer program is settled such that the planar kinematic chains catalogue with degrees of freedom the given number of links and can be synthesized automatically. Karouia and Herve [3] addressed about synthesis of asymmetrical non-over constrained spherical parallel mechanism (SPM). To find out the degrees of freedom of limbs mobility analysis is used.

Sariyildiz et. al. [4] presented a paper on comparison of three inverse kinematic methods of serial industrial robots. The comparison mainly based on the screw theory. Llyod and Hayward [5] described about an approach for simple manipulator to find the mathematical solution. Milicevic et. al. [6] addressed about development of robot models and simulation of its kinematics and dynamics by using the MAT Lab tool box. They used 4*4matrix for homogeneous transformation and the robot links are having rotational and translational motion. Singh et. al. [7] provides a review of the robotics and they discussed about the inverse kinematics of two links and three links of a robotic system. Hayawi [8] discussed about TR 4000 educational robot arm of having 5- DOF and its kinematic solutions. Later a software program is interfaced to show the robot motion with respect to its mathematical analysis. Sharma et. al. [9] developed an inverse kinematic solution for 6- DOF KUKA robot by using the D-H notations. They established a relationship between the reliability and repeatability of a robot by using the experimental analysis. Kumar et. al. [10] developed a method for trajectory planning for welding application and forward and inverse kinematic analysis has been performed for 6-DOF KUKA robot. Parhi and Deepak [11] developed a 5-axis articulated robot manipulator. Forward kinematic analysis of a 5-axis articulated robot has been performed to know the end effector position of pick and place robot.

2.2. Welding

Welding is basic joining process of materials like thermoplastics and metals with or without application of heat and with or without application of pressure. Welding joints are permanent and they give good strength compared with other joints. The span and quality of the welded joints are decided by welding parameters like voltage, current, electrode size, and weld travel speed. Optimum combination of the welding parameters gives good weld bead strength.

Lu et al. [12] were described about how to improve the weld penetration of a double shielded TIG method and under various welding parameters (i.e. speed, arc length, and current) it has been compared with the traditional TIG welding method. They examined weld pool shape variation on a ZGOCr13Ni5Mo Martensitic stainless plate under two different methods of TIG welding. The influence of welding parameters (arc length, speed and current) on weld pool shape are discussed under both the double shielded TIG and traditional TIG process. Juang and Tarang [13] discussed about the selection of process parameters of TIG welding of stainless steel plates to obtain the optimum weld pool quality. The weld pool quality characteristics are like back height, back width, front height and front width. They have been chosen the Taguchi method to relate the welding parameters and weld pool quality characteristics in order to get optimum weld quality. Tham et al. [14] developed a correlation between the weld bead geometry and welding parameters like arc voltage, welding current and welding speed of 3F T-fillet geometry. They conducted the experiments and developed a calculator for any values of welding parameters to display the weld bead geometry values and vice versa. The error between actual experimental results and the predicted weld bead geometry is less than 1.00 mm, it has been validated accurately. Praveen et al. [15] investigated about the GMAW and incorporating additional complexity like base current, peak current, base time, peak time, frequency and duty cycle which requires correctly defining the pulse parameters in order to get good quality. To get better weld quality and minimum weld defects one droplet should be separated with other. A model has been developed to estimate number of drops transferred to the work piece from the end of the electrode.

2.3. Robot Welding

Robot welding is an automated welding which reduces the human effort and errors. It is a quick and accurate process. In this, robots are consists of so many links and joints. A welding tool or welding gun is attached to the end effector. A wide literature has been collected regarding the automated programme for welding operation.

Pires et. al. [16] developed a solution for extracting the information of a robot from the CAD data. Industrial robots play a vital role in industries for many applications, because of their flexibility in working. As soon as welding is performed by robots, the issues may come like programming problems. In this paper, they described issue by giving a CAD interface assisting simple and fast programming. Neto et.al. [17] developed CAD based high – level programme for a robot. From the CAD drawing, directly we can get robot programs on a generally available 3D CAD packages. They designed simple programme which does not requires advanced programming skills and low- set up system and low cost.

Neto and pires [18] developed a new system of simulation where commercially available and low cost 3D CAD package is used for pre-programmed robot paths simulation. The simulator is adequately used for educational purpose and small and medium sized enterprises. They conducted the experiments and validated with offline results. Pires et. al. [19] developed CAD based system to program a robot from 3D CAD model, permitting the users to write off line programs, without stop the robot production. Pan et.al. [20] Presented a robotic automated offline programming (AOLP) for welding operation. AOLP is software which takes a CAD file as a input and gives robotic welding codes for programming as a output with high degree of freedoms.

Chang et. al. [21] proposed algorithm is to detect the seam of single butt welding with manually track welded non -zero gaps. The algorithm consists of four steps – generation of the reference points, scanning, filtering and the path planning. In scanning process, the cross section depth data of the seam profile is obtained. Next a gussian filter is used to remove noise from the raw data. A differential characteristics point detection algorithm is applied to the filtered data to detect the reference point that represent the location of the gap and shape to be welded. Finally for single V butt multi pass welding, path planning is done based on the detected reference points.

Hong et. al. [22] defined about real – time visual measurement of a welding robot system in the different levels of the welding current. The principal objective is to measure the offset of the torch to the seam centre and the size of seam gap by track the seam, passive vision and control the weld pool in real time. Benyounis and Olabi [23] discussed about welding input parameters play a very important role in determining the weld joint quality. The quality of joint can be well-defined in terms of properties such as weld-bead geometry, mechanical properties, and distortion. Kim et. al. [24] was observed that the process parameters like current, wire feed rate, voltage, and welding speed and torch angle affect the bead geometry and the quality of the weld. Commonly input parameters are independent and quality of weld is influenced by them. Therefore, welding can be considered as a multi-input and multi-output process.

2.4. Summary

This section addresses the related literature review on the robot kinematics, which includes forward kinematics and inverse kinematics. After that this work is extended to gather literature on the welding and its parameters. The literature describes how the kinematic equations are modelled and how the welding parameters influencing the weld path. Later the literature enhances to robot welding which addresses how to write the programme for simulation of a robot. In this, section, an automated off-line programs has been developed to extract CAD data and to perform welding operation.

Chapter 3

MECHANICAL DESIGN ARCHITECTURE OF THE ROBOT ARM

Rotation Kinematics

Forward Kinematic Analysis

Forward Kinematic Analysis

Summary

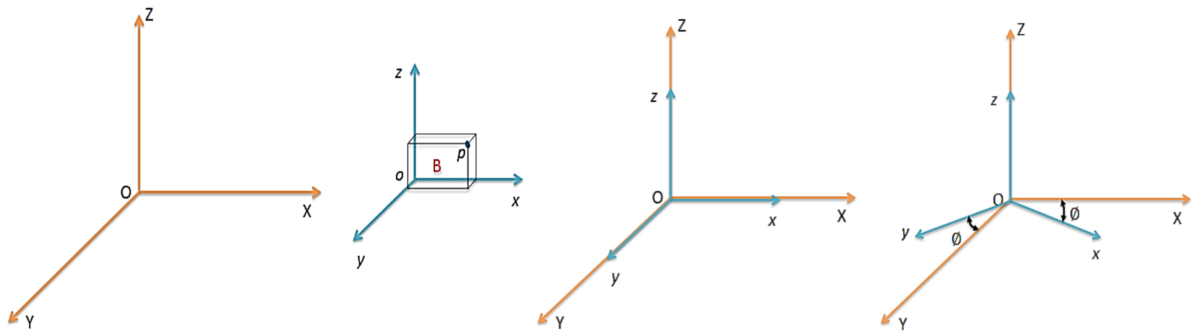
3. MECHANICAL DESIGN ARCHITECTURE OF ROBOT WELDING

Manipulator kinematics pacts with the motion of robot arm with respect to the fixed frame of reference without considering the forces or moments which cause the motion of the robot arm. Manipulator kinematics includes forward kinematic analysis as well as inverse kinematic analysis. In forward kinematic analysis for given link lengths and joint angles we have to find out the position and orientation of the end effector with respect to fixed reference frame. Where as in the inverse kinematic analysis for a given position and orientation of end effector we have to obtain joint parameters.

3.1. Rotation Kinematics

A robotic system consists of links and they are modelled like rigid bodies. Therefore, rigid body features are no displacement in the body and take a vital role in robotics. As the robot links may rotate / translate with respect to each other, it is required to find their relative configurations with respect to world reference frame. The relative position between link B and link A is well-defined by a coordinate transformation ${}^{A}T_{B}$ between attached link reference frames.

Consider a rigid body B and a global coordinate frame OXYZ with a local coordinate frame oxyz as shown in Fig.3.1(a). Primarily the body B is fixed to the ground G and their reference frames are coinciding at Point O as represented in Fig. 3.1(b).



(a) (b) (c)

Fig.3.1 a) Global & Local Coordinate frames, b) Initial frames position and c) Local frame rotation with respect to global frame

In the global coordinate frame the rigid body B rotates about the Z-axis and making an angle of ∅ degrees as shown in Fig. 3.1(c), then body point P coordinates in the global and local coordinate frames are given by the Eq. (3.1).

$$G(p) = R(Z, \emptyset)B(p) \tag{3.1}$$

Here $R(Z, \emptyset)$ is rotational mapping matrix

$$G(p) = \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} \text{ and } B(p) = \begin{Bmatrix} x \\ y \\ z \end{Bmatrix}$$

Let (i_X, j_Y, k_Z) and (i_x, j_y, k_z) be the unit vectors along the coordinate axes of the OXYZ global coordinate system and oxyz local coordinate systems respectively.

$p_{XYZ} = Xi_X + Yj_Y + Zk_Z = xi_x + yj_y + zk_z = p_{xyz}$

The point p can be defined by using the definition of scalar product as the components of a vector as represented in Eq. (3.2).

$$\left.\begin{aligned} X &= i_X . p = i_X . i_x x + i_X . j_y y + i_X . k_z z \\ Y &= j_Y . p = j_Y . i_x x + j_Y . j_y y + j_Y . k_z z \\ Z &= k_W . p = k_W . i_x x + k_W . j_y y + k_W . k_z z \end{aligned}\right\} \tag{3.2}$$

$$\Rightarrow \begin{Bmatrix} p_X \\ p_Y \\ p_Z \end{Bmatrix} = \begin{bmatrix} i_X . i_x & i_X . j_y & i_X . k_z \\ j_Y . i_x & j_Y . j_y & j_Y . k_z \\ k_W . i_x & k_W . j_y & k_W . k_z \end{bmatrix} \begin{Bmatrix} p_x \\ p_y \\ p_Z \end{Bmatrix}$$

$$= \begin{bmatrix} cos(\emptyset) & cos(90 + \emptyset) & cos(90) \\ cos(90 - \emptyset) & cos(\emptyset) & cos(90) \\ cos(90) & cos(90) & cos(0) \end{bmatrix} \begin{Bmatrix} p_x \\ p_y \\ p_Z \end{Bmatrix}$$

$$= \begin{bmatrix} cos(\emptyset) & -sin(\emptyset) & 0 \\ \sin(\emptyset) & cos(\emptyset) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} p_x \\ p_y \\ p_Z \end{Bmatrix}$$

From the above mapping matrix can be written as, $R(Z, \emptyset) = \begin{bmatrix} cos(\emptyset) & -sin(\emptyset) & 0 \\ sin(\emptyset) & cos(\emptyset) & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

Accordingly the global coordinates of the point p can be obtained by rotation $\emptyset$ angle with respect to X- axis and Y- axis in local coordinate frames and the transformations are represented by Eqs. (3.3) & (3.4).

$$R(X,\emptyset) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\emptyset) & -sin(\emptyset) \\ 0 & \sin(\emptyset) & cos(\emptyset) \end{bmatrix} \tag{3.3}$$

$$R(Y,\emptyset) = \begin{bmatrix} cos(\emptyset) & 0 & sin(\emptyset) \\ 0 & 1 & 0 \\ -sin(\emptyset) & 0 & cos(\emptyset) \end{bmatrix} \tag{3.4}$$

To denote rotations about the principal axes of OXYZ coordinate system the basic rotation matrices should be sequentially multiplied. Since matrix multiplications are not commute, the order of performing rotations is important.

3.2. Forward Kinematic Analysis

Forward kinematics or direct kinematics of the manipulator is used to find out the position and orientation of the end-effector for a known joint angles and link parameters. Manipulator consists of so many parts the positions can be calculated with respect to the different reference frames. An analysis of the links at different position is methodically calculated. Schematic diagram for the direct kinematics of a manipulator is represented in Fig. 3.2.

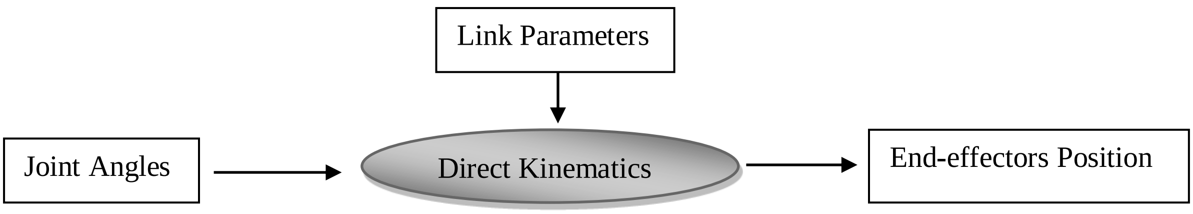


Fig.3.2 Schematic diagram of direct kinematics of a manipulator

Coordinate frames for the manipulator are assigned as shown in the Fig.3.3. Table 3.1 shows the values of links and joints.

Specification	**Value**	**Units**
Number of axes	3	
No of Links	3	
Lengths of Link1, Link 2 and Link 3	70,100,70	mm
Work Envelope	Body Rotation : 360 Elbow Rotation :180,-180 Wrist Rotation : 90,270	degrees

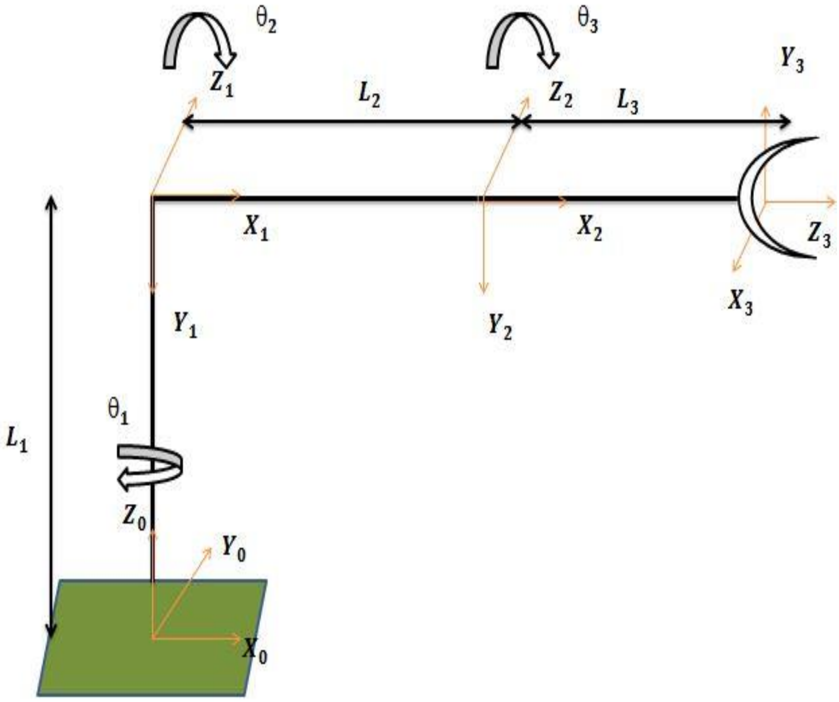


Fig.3.3 Link coordinate frame of the manipulator

The kinematic information includes: position, velocity, acceleration, and jerk. However, forward kinematics generally refers to position analysis. So the forward kinematic analysis is equivalent to a determination of a combined transformation matrix and it is represented in Eq. (3.5) & Eq. (3.6).

$$T_i = Rot(z,\theta_i) * Rot(x,\theta_i) * Rot(x,\theta_i) \tag{3.5}$$

$$T_3^0 = T_0^1 * T_1^2 * T_2^3 \tag{3.6}$$

Where the first transformation matrix is represented in Eq. (3.7)

$$T_0^1 = \begin{bmatrix} cos\theta_1 & -sin\theta_1 & 0 & l_1 cos\theta_1 \\ sin\theta_1 & cos\theta_1 & 0 & l_1 sin\theta_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.7}$$

The second transformation matrix to relate the first frame to second frame is represented in Eq. (3.8)

$$T_1^2 = \begin{bmatrix} cos\theta_2 & -sin\theta_2 & 0 & l_2 cos\theta_2 \\ sin\theta_2 & cos\theta_2 & 0 & l_2 sin\theta_2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.8}$$

The third transformation matrix which relates the second frame and end-effector frame which can be represented by Eq. (3.9),

$$T_2^3 = \begin{bmatrix} cos\theta_3 & -sin\theta_3 & 0 & l_3 cos\theta_3 \\ sin\theta_3 & cos\theta_3 & 0 & l_3 sin\theta_3 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.9)$$

Therefore, the transformation matrix to relate the end-effector frame to the base frame is represented by Eq. (3.10)

$$T_0^3 = \begin{bmatrix} \cos(\theta_1 + \theta_2 + \theta_3) & -sin(\theta_1 + \theta_2 + \theta_3) & 0 & r_{14} \\ \sin(\theta_1 + \theta_2 + \theta_3) & \cos(\theta_1 + \theta_2 + \theta_3) & 0 & r_{24} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.10)$$

Where, $r_{14}$and r_{24} are represented by Eq. (3.11) & Eq. (3.12)

$$r_{14} = l_1 cos\theta_1 * (l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3)) \quad (3.11)$$

$$r_{24} = l_1 sin\theta_1 * (l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3)) \quad (3.12)$$

We can find the coordinate of the tip point in the base Cartesian coordinate frame if we have the geometry of the robot and all joint variables.

$$X = l_1 cos\theta_1 * (l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3))$$

$$Y = l_1 sin\theta_1 * (l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3))$$

3.3. Inverse Kinematic Analysis

In a robotic arm some of the independent variables are there like joint variables they will change with respect to the different reference frames. In an inverse kinematic problem by knowing the position of the end-effector we have to obtain the joint variables. In general, there are so many methods to solve the inverse kinematic problem such as analytical/ geometrical approach, iterative approach and matrix algebraic approach. Schematic diagram of inverse kinematics represented in Fig 3.4. Fig 3.5 shows the elbow, wrist position for the same end effector position.

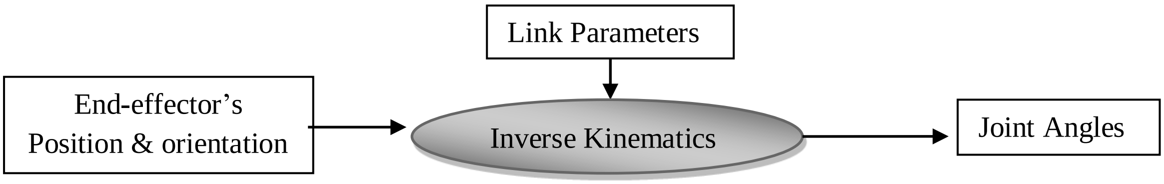


Fig.3.4. Schematic diagram of inverse kinematics of a manipulator

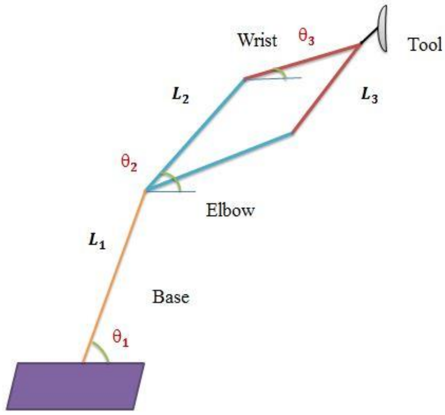


Fig.3.5 Elbow position & Wrist position for the same end-effector position

By observing the Eq. (3.17), there is a possibility of getting two wrist angles ($\pm\theta_3$) for the same tool position. Since the elbow angle (θ_2) depends on wrist angle (θ_3), there will be two elbow angles corresponds to each wrist angle as shown in the Fig.3.9.

This section describes the development of inverse kinematic models of an arm based on its link coordinate systems.

The base angle can be determined by Eq. (3.13)

Base angle $\theta_1 = arctan\left({}^{p_y}/_{p_x}\right)$ (3.13)

Where, p_x and p_y can be found from Eq. (3.11) & Eq. (3.12)

After finding the base angle the 3R problem can be converted into 2R planar problem. The two links are elbow and wrist and the two wrist angles can be found ($\pm\theta_3$) for the same tool position.

The inverse kinematics of the planar robots is generally easier to find analytically. The manipulator tip point global position is represented by Eq. (3.14) & Eq. (3.15)

$$Y = l_2 cos\theta_2 + l_3 \cos(\theta_2 + \theta_3) \quad (3.14)$$

$$Z = l_2 sin\theta_2 + l_3 \sin(\theta_2 + \theta_3) \quad (3.15)$$

Therefore

$$Y^2 + Z^2 = l_2^2 + l_3^2 + 2l_2l_3cos\theta_3$$

$$cos\theta_3 = \frac{Y^2 + Z^2 - l_2^2 - l_3^2}{2l_2l_3}$$

θ_3 can be represented by Eq. (3.16)

$$\theta_3 = cos^{-1}\left(\frac{Y^2+Z^2-l_2^2-l_3^2}{2l_2l_3}\right) \qquad (3.16)$$

To find θ_2 using atan2 function is represented by Eq. (3.17)

$$\theta_3 = \pm atan2\sqrt{\frac{(l_2+l_3)^2-(Y^2+Z^2)}{(Y^2+Z^2)-(l_2-l_3)^2}} \qquad (3.17)$$

The $\pm$ is because of the square root, which gives two solutions. These two solutions are called as elbow up and elbow down.

The joint angle θ_2 for elbow up position is given by Eq. (3.18) and for elbow down position is given by Eq. (3.19)

$$\theta_2 = atan2\frac{Z}{Y} + atan2\left(\frac{l_3sin\theta_3}{l_2 + l_3\cos\theta_3}\right) \qquad (3.18)$$

$$\theta_2 = atan2\frac{Z}{Y} - atan2\left(\frac{l_3sin\theta_3}{l_2 + l_3\cos\theta_3}\right) \qquad (3.19)$$

3.4. Summary

The aim of current section is to understand the robot arm structure motion. The motion of the manipulator is studied in two ways, forward kinematics and inverse kinematics. Forward kinematic analysis is to obtain position of the end effector by knowing the joint angles and link parameters. In inverse kinematic analysis by knowing the position of the manipulator and link parameters it is very easy to find out joint angles. Arm equation has been developed for 3-axis robot by using the forward kinematic model. From the developed arm equation, to obtain joint parameters inverse kinematic model has been developed.

Chapter 4

METHDOLOGY FOR CAD ASSISTED ROBOT WELDING

4. METHDOLOGY FOR CAD ASSISTED ROBOT WELDING

At present, robots are extensively used for performing welding operation for increasing the quality of the weld as well as for better production rate. In the current section, robot has to perform welding operation in CAD environment/ virtual environment. Extraction of the coordinate data from the existed geometry can be possible by writing program in CATIA.

4.1. Manipulator Design in CATIA

This robot is a 3 axis robot which consists of three links as well as three joints. Three links of manipulator namely base link, shoulder link, and wrist link. Link 1 is fixed on the base and it will rotate about Z- axis. Link 1 and link 2 are connected by revolute joint and link 2 will rotate about X-axis. Link 2 and link 3 are connected by revolute joint and link 3 will rotate about X- axis. Connections between the links are represented in the Fig.4.1. On a robot end-effector link welding gun has to be attached to perform the welding operation for specified seam position.

The forward and inverse kinematic analysis has been performed. Forward kinematic analysis is used for finding the position of an end effector by knowing the joint angles. Inverse kinematics is used for finding the joint angles from the given position of an end effector.

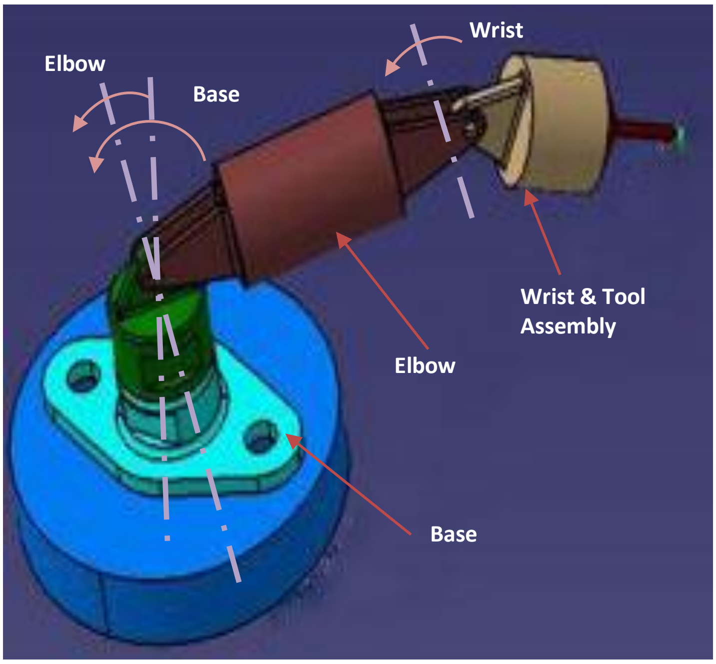
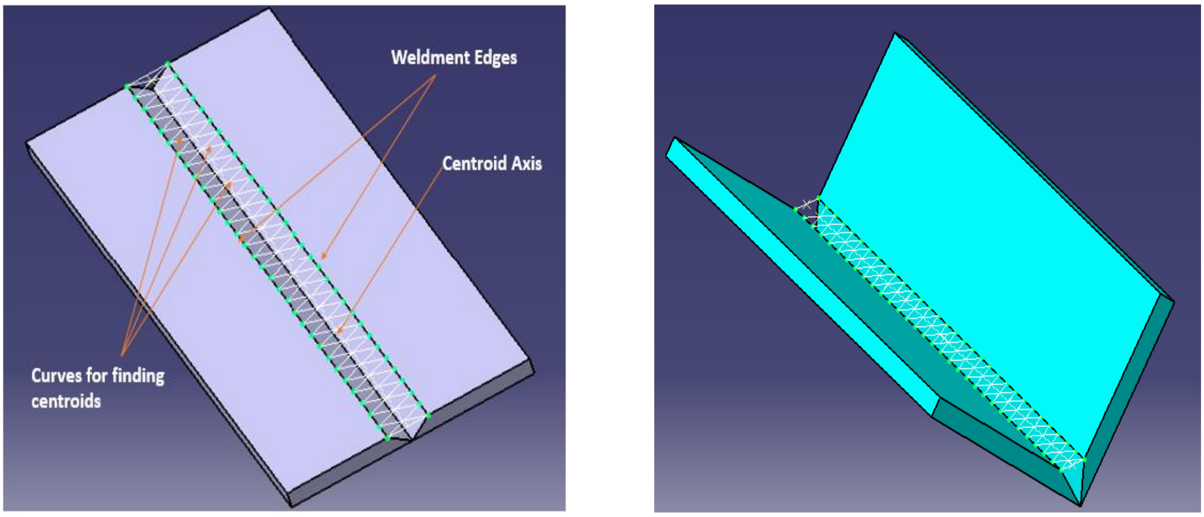


Fig. 4.1 CATIA model of 3-axis robot arm

4.2. Extracting Coordinate Data from CAD Geometry of Welded Joints

From the existed CAD model, it is very easy to know the geometry where to be welded. In this approach, control points are considered along the length/ periphery of the welding joint. The control points of opposite edges are connected by a curve and along the entire length we have to draw the curves. These curves representation is shown in Fig.4.2. By joining the centroids of each curve we will get a path that path is nothing but weld seam path. This technique is known as sewing technique and it can be modelled by generative shape design module in CATIA. By knowing weld seam coordinates it is very easy to obtain the joint angles of a robot. Finally along the weld seam path and it will perform the welding operation.



(a) (b)

Fig.4.2. Sewing diagram in CATIA for butt and l shape weld joint

From the diagram, we can observe that weld seam path can be obtained by using the centroids of the each curve. The procedure for the butt joint as well as L-shape joint is same. By knowing the weld seam it is very easy to weld the any profile. After extracting the coordinate data, we can import the data into Excel and after we can find the inverse kinematic solution for particular weld seam path.

Table.1. shows the point coordinate data of weld seam path.

S. No.	X	Y	Z	S. No.	X	Y	Z
1	120	90	80	16	1.034483	105.5172	61.89655
2	112.069	91.03448	78.7931	17	-6.89655	106.5517	60.68966
3	104.1379	92.06897	77.58621	18	-14.8276	107.5862	59.48276
4	96.2069	93.10345	76.37931	19	-22.7586	108.6207	58.27586
5	88.27586	94.13793	75.17241	20	-30.6897	109.6552	57.06897
6	80.34483	95.17241	73.96552	21	-38.6207	110.6897	55.86207
7	72.41379	96.2069	72.75862	22	-46.5517	111.7241	54.65517
8	64.48276	97.24138	71.55172	23	-54.4828	112.7586	53.44828
9	56.55172	98.27586	70.34483	24	-62.4138	113.7931	52.24138
10	48.62069	99.31034	69.13793	25	-70.3448	114.8276	51.03448
11	40.68966	100.3448	67.93103	26	-78.2759	115.8621	49.82759
12	32.75862	101.3793	66.72414	27	-86.2069	116.8966	48.62069
13	24.82759	102.4138	65.51724	28	-94.1379	117.931	47.41379
14	16.89655	103.4483	64.31034	29	-102.069	118.9655	46.2069
15	8.965517	104.4828	63.10345	30	-110	120	45

4.3. Inverse Kinematic Solution

In inverse kinematic solution, for the known link lengths and position of end-effector it is very easy to obtain joint angles. By using the equations we will find the base angle (θ_1) and after that 3R problem can be converted into 2R problem. An Excel sheet has been prepared to find out the all the joint angles. Two combinations of elbow angle (θ_2), and wrist angle (θ_3) can be obtained from the inverse kinematic model equations.

4.4. Summary

This chapter describes the modeling of robot which is having three links and three joints. For each and every joint is having rotary motion with respect to other joint. Extraction of existed geometry data by using the sewing technique and that data is given input to the Excel. An inverse kinematic solution has been developed for the existed coordinate data which is used for simulation of weld seam path and validation of weld seam path.

Chapter 5

EXPERIMENTAL ANALYSIS

CAD Program for Inverse Kinematic Solution

Robot Welding Simulation and Validation

Summary

5. EXPERIMENTAL ANALYSIS

In experimental analysis, a program has been generated for inverse kinematic solution. This program is written by using VB script. Robot welding operation simulation and its validation is described in this current section.

5.1. CAD program for Inverse Kinematic Solution

An inverse kinematic solution has been obtained in the previous chapter. A program has been developed for simulation of the robot welding operation. This program mainly consists of joint angle data. Two combinations of elbow and wrist angles are there so two set of simulation results will come. The program for simulation is mentioned below.

```
Sub CATMain ()

Set

productDocument1 = CATIA.

Active Document

Set product1 = productDocument1.Product

Set constraints1 = product1.Connections ("CATIAConstraints")

Set constraint1 = constraints1.Item ("Angle.5")

Set constraint2 = constraints1.Item("Angle.8")

Set constraint3 = constraints1.Item ("Angle.11")

Dim a(36),b(66),c(66), d(66),e(66)

a(1)=-44.6879607165548

a(2)=-44.0610476574357

a(3)=-42.089399674073

a(4)=-39.9871213306869

a(5)=-37.7470365081098

a(6)=-35.3626872366224

a(7)=-32.8287592987374

a(8)=-30.1415928865617

a(9)=-27.2997668063535

a(10)=-24.3047283665792
```

a(11)=-21.1614205559446

a(12)=-17.8788361000645

a(13)=-14.4704096232035

a(14)=-10.9541517190568

a(15)=-7.35243995930971

a(16)=-3.69141666294702

a(17)=-0.000477464829259588

a(18)=3.69141666294702

a(19)=7.35243995930971

a(20)=10.9541517190569

a(21)=14.4704096232035

a(22)=17.8788361000645

a(23)=21.1614205559447

a(24)=24.3047283665792

a(25)=27.2997668063535

a(26)=30.1415928865617

a(27)=32.8287592987374

a(28)=35.3626872366224

a(29)=37.7470365081098

a(30)=39.9871213306869

a(31)=42.089399674073

a(32)=44.0610476574357

b(1)=165.825071044419

b(2)=172.825071044419

b(3)=181.703873497864

b(4)=185.971980109865

b(5)=189.04607241603

b(6)=191.451370072378

b(7)=193.397740540884

b(8)=194.995201561828

b(9)=196.310918471732

b(10)=197.390439583882

b(11)=198.267191740372

b(12)=198.967160998307

b(13)=199.511255610286

b(14)=199.916414045598

b(15)=200.195991304652

b(16)=200.359746183704

b(17)=200.41365851913

b(18)=200.359746183704

b(19)=200.195991304652

b(20)=199.916414045598

b(21)=199.511255610286

b(22)=198.967160998307

b(23)=198.267191740372

b(24)=197.390439583882

b(25)=196.310918471732

b(26)=194.995201561828

b(27)=193.397740540884

b(28)=191.451370072378

b(29)=189.04607241603

b(30)=185.971980109865

b(31)=181.703873497864

b(32)=172.8250710444

c(1)=172.337005252495

c(2)=172.688886951353

c(3)=150.193760122168

c(4)=138.773964783458

c(5)=130.171851762275

c(6)=123.134882466779

c(7)=117.174628133133

c(8)=112.046492736279

c(9)=107.612407128928

c(10)=103.789554196794

c(11)=100.527018145683

c(12)=97.7935811809506

c(13)=95.5706250700063

c(14)=93.8476307168955

c(15)=92.619141998732

c(16)=91.8826629467221

c(17)=91.637245081872

c(18)=91.8826629467221

c(19)=92.619141998732

c(20)=93.8476307168955

c(21)=95.5706250700063

c(22)=97.7935811809506

c(23)=100.527018145683

c(24)=103.789554196794

c(25)=107.612407128928

c(26)=112.046492736279

c(27)=117.174628133133

c(28)=123.134882466779

c(29)=130.171851762275

c(30)=138.773964783458

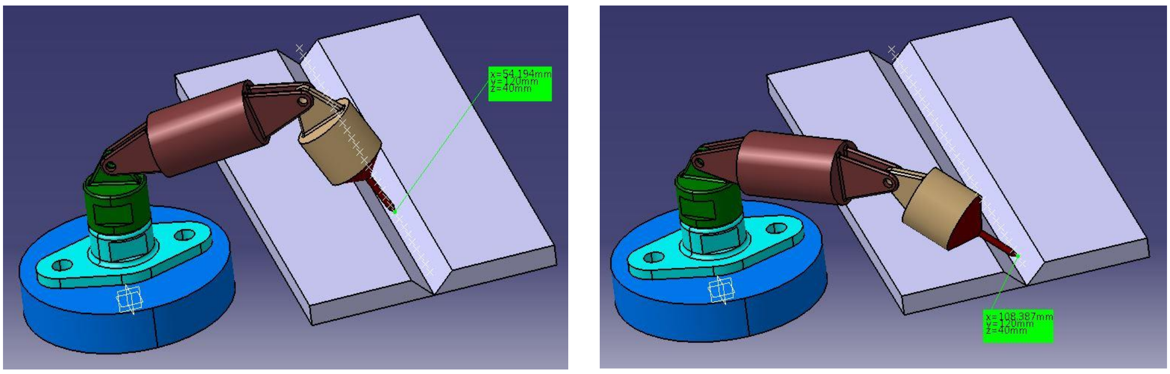
c(31)=150.193760122168

c(32)=172.688886951353

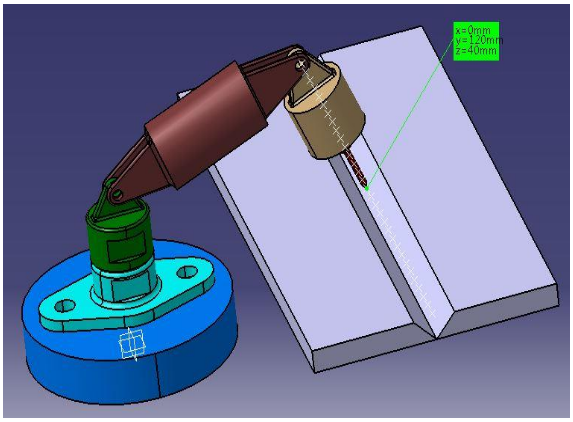
```
For i= 3to 30

Set angle1 = constraint1.Dimension

angle1.Value = a(i)

product1.Update

Set angle2 = constraint2.Dimension

angle2.Value = b(i)

product1.Update

Set angle3 = constraint3.Dimension

angle3.Value = c(i)

product1.Update

Next

End Sub
```

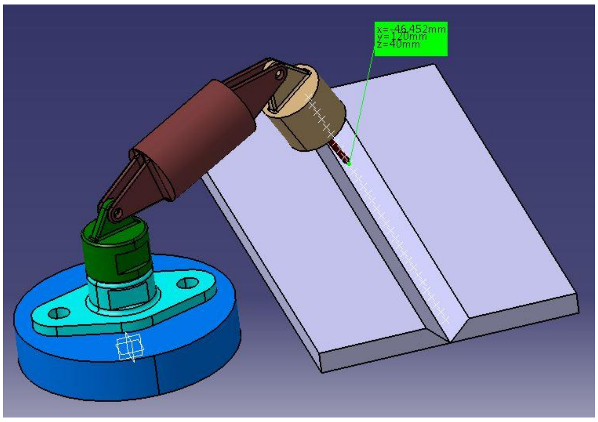
5.2. Robot simulation and Its Validation

From the kinematics, the base angle and the other two sets of elbow and wrist angles are known. For those two sets, the robot simulation has been performed. In simulation, the robot will move along the seam path given from sewing technique. Different point coordinate representations are shown in Fig. 5.1. Fig. 5.1 (a) - (d) presents coordinate representation for one set of feasible combination and Fig. 5.1 (e) – (h) shows representation of second set of unfeasible combination.

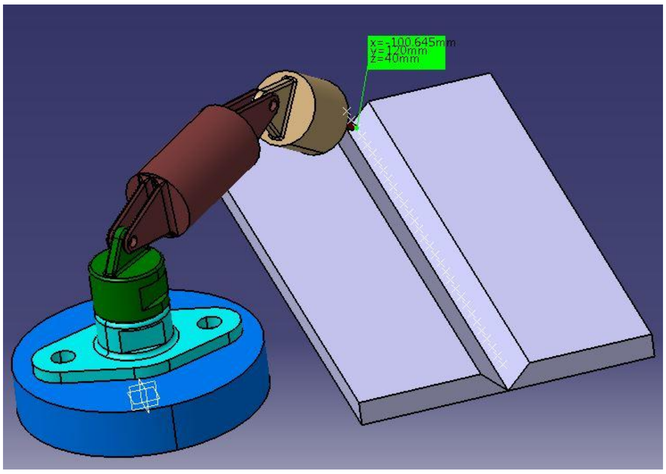


(a) (b)



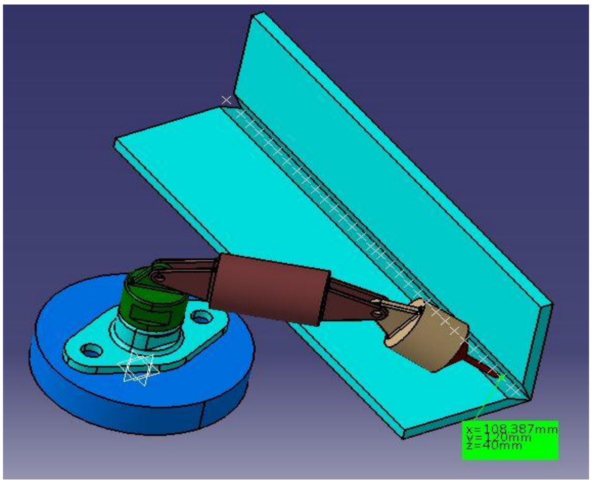


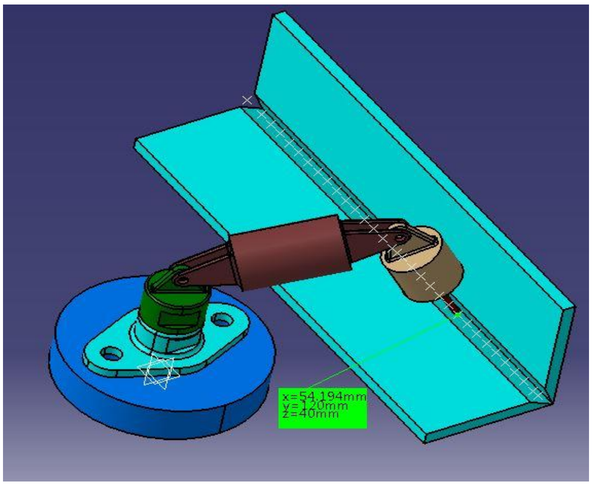
(c) (d)



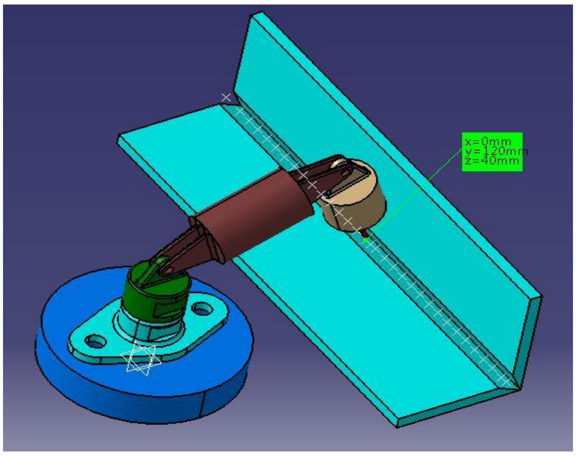
(e)

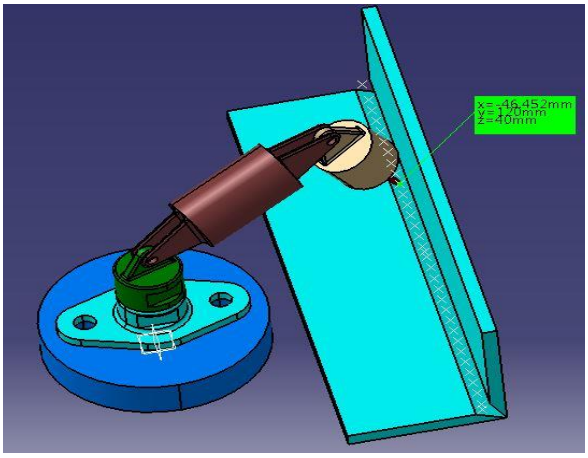
Fig 5.1. Point co-ordinate representation of robot for butt joint



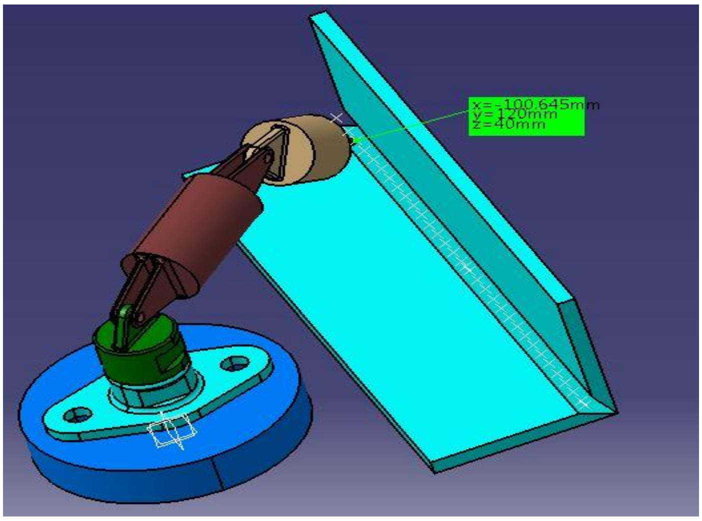


(a) (b)





(c) (d)



(e)

Fig 5.1. Point co-ordinate representation of robot for L joint

Trajectory planning for weld seam path is given by

- The obtained geometric path (seam path) and kinematic constraints will be given as input to the developed robotic arm for performing welding operation.
- In this analysis the trajectory planning is performed according to the 3^{rd} order cubic spline interpolation.

For the cubic spline trajectory

$$H(t) = a1 * t^3 + a2 * t^2 + a3 * t + a4$$

The constant values can be obtained while subjected to following boundary conditions:

- At *t=0*, $a4 = \theta_0\ (given)\ and\ v_0 = a3/t$

- At t=1, $a1 + a2 + a3 + \theta_0 = \theta_f$
- $v_f = (3a1 * t^2 + 2a2 * t + a3)/t$
- $a_f = (6a1 * t + 2a2)/t^2$

5.3. Summary

A CAD program has been developed for simulation of the robot welding. From inverse kinematic solution joint angles are obtained and that joint angles are given as an input to the program. Due to that robot simulation has been performed for two combinations like elbow up and elbow down position. In the solution, elbow up solution is feasible and elbow down position makes an interference with the robot links. Robot simulation path has been validated.

Chapter 6

CONCLUSION AND FUTURE SCOPE

Conclusion

Future Scope

6. CONCLUSION AND FUTURE SCOPE

This thesis work investigation has been carried out to simulate the weld seam path using the robotic arm in CAD environment. Robot arm consists of three links and three joints. The joints are all rotary in nature. First 3D CAD model has been created after that kinematic analysis has been performed. Inverse kinematic solution has been developed by using an Excel sheet and that data is given to CAD model as input file program.

9.1. Conclusions

The conclusions drawn from the current investigation are depicted below:

- A 3-axis robotic arm has been modelled using CAD tool for performing welding operations. For the developed robotic arm, forward & inverse kinematic analyses have been performed to move the weld torch in the desired trajectory.
- A new seam tracking methodology, named sewing technique has been introduced for the welded joints available in Computer Aided Design (CAD) environment.
- This methodology, gives the seam path by drawing a line through the adjacent centroids of curve fitted in the weld joint volume. Obtained geometric path and kinematic constraints are given as input to the modelled robot for performing welding operation followed by desired trajectory.
- Validation of the developed methodology has been done through simulation results while performing welding operations for different weld profiles.

9.2. Future Scope

The focus of this thesis is on modeling of 3-axis robot arm, kinematic analysis of robot, inverse kinematic solution, program for inverse kinematic solution and simulation of the robot arm through the specified seam path. The following list of motivating advices to pursue as future work by refining the condition of art immediately related to this work.

- Robot welding simulation has been performed using 3-axis robot arm in CAD environment. So, CAD environment is a virtual environment. As a future work, robot welding has to be performed in the real time environment.

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APPENDIX-A

S NO	X	Y	Z	L1	L2	L3	q1	Nt1	Nt1	x	y	z		Nt3	Nt3	Nt3	Nt3			Nt2	Nt2	Nt2	
1	120	90	80	70	100	70	36.87	-53.1	53.13	0	150	10	56.6	56.63	-56.63	236.63	123.37	3.8141	22.88	26.7	-19.07	206.7	160.93
2	112.07	91.034	78.79	70	100	70	39.09	-50.9	50.91	0	144.4	8.79	64.5	64.51	-64.51	244.51	115.49	3.4851	25.9	29.39	-22.42	209.39	157.58
3	104.14	92.069	77.59	70	100	70	41.48	-48.5	48.52	0	139	7.59	71.3	71.34	-71.34	251.34	108.66	3.1239	28.45	31.58	-25.33	211.58	154.67
4	96.207	93.103	76.38	70	100	70	44.06	-45.9	45.94	0	133.9	6.38	77.4	77.36	-77.36	257.36	102.64	2.728	30.64	33.36	-27.91	213.36	152.09
5	88.276	94.138	75.17	70	100	70	46.84	-43.2	43.16	0	129.1	5.17	82.7	82.69	-82.69	262.69	97.31	2.2952	32.52	34.81	-30.22	214.81	149.78
6	80.345	95.172	73.97	70	100	70	49.83	-40.2	40.17	0	124.6	3.97	87.4	87.43	-87.43	267.43	92.574	1.8236	34.14	35.96	-32.31	215.96	147.69
7	72.414	96.207	72.76	70	100	70	53.03	-37	36.97	0	120.4	2.76	91.6	91.61	-91.61	271.61	88.392	1.3124	35.52	36.83	-34.2	216.83	145.8
8	64.483	97.241	71.55	70	100	70	56.45	-33.5	33.55	0	116.7	1.55	95.3	95.26	-95.26	275.26	84.739	0.7619	36.68	37.44	-35.92	217.44	144.08
9	56.552	98.276	70.34	70	100	70	60.08	-29.9	29.92	0	113.4	0.34	98.4	98.39	-98.39	278.39	81.606	0.1742	37.64	37.82	-37.47	217.82	142.53
10	48.621	99.31	69.14	70	100	70	63.91	-26.1	26.09	0	110.6	-0.86	101	101	-101	281.01	78.994	-0.447	38.42	37.97	-38.87	217.97	141.13
11	40.69	100.34	67.93	70	100	70	67.93	-22.1	22.07	0	108.3	-2.07	103	103.1	-103.1	283.09	76.909	-1.095	39.02	37.92	-40.11	217.92	139.89
12	32.759	101.38	66.72	70	100	70	72.09	-17.9	17.91	0	106.5	-3.28	105	104.6	-104.6	284.64	75.36	-1.761	39.45	37.69	-41.21	217.69	138.79
13	24.828	102.41	65.52	70	100	70	76.37	-13.6	13.63	0	105.4	-4.48	106	105.6	-105.6	285.64	74.357	-2.436	39.72	37.29	-42.16	217.29	137.84
14	16.897	103.45	64.31	70	100	70	80.72	-9.28	9.276	0	104.8	-5.69	106	106.1	-106.1	286.09	73.908	-3.107	39.84	36.74	-42.95	216.74	137.05
15	8.9655	104.48	63.1	70	100	70	85.1	-4.9	4.904	0	104.9	-6.9	106	106	-106	285.99	74.015	-3.763	39.82	36.05	-43.58	216.05	136.42
16	1.0345	105.52	61.9	70	100	70	89.44	-0.56	0.562	0	105.5	-8.1	105	105.3	-105.3	285.32	74.678	-4.391	39.64	35.24	-44.03	215.24	135.97
17	-6.897	106.55	60.69	70	100	70	-86.3	3.703	-3.7	0	106.8	-9.31	104	104.1	-104.1	284.11	75.892	-4.983	39.3	34.32	-44.29	214.32	135.71
18	-14.83	107.59	59.48	70	100	70	-82.2	7.847	-7.85	0	108.6	-10.5	102	102.4	-102.4	282.35	77.648	-5.531	38.81	33.28	-44.34	213.28	135.66
19	-22.76	108.62	58.28	70	100	70	-78.2	11.83	-11.8	0	111	-11.7	100	100.1	-100.1	280.06	79.937	-6.031	38.14	32.11	-44.17	212.11	135.83
20	-30.69	109.66	57.07	70	100	70	-74.4	15.64	-15.6	0	113.9	-12.9	97.2	97.25	-97.25	277.25	82.75	-6.479	37.3	30.82	-43.77	210.82	136.23
21	-38.62	110.69	55.86	70	100	70	-70.8	19.23	-19.2	0	117.2	-14.1	93.9	93.92	-93.92	273.92	86.083	-6.876	36.26	29.38	-43.13	209.38	136.87
22	-46.55	111.72	54.66	70	100	70	-67.4	22.62	-22.6	0	121	-15.3	90.1	90.06	-90.06	270.06	89.938	-7.225	35.01	27.79	-42.24	207.79	137.76

23	-54.48	112.76	53.45	70	100	70	-64.2	25.79	-25.8	0	125.2	-16.6	85.7	85.67	-85.67	265.67	94.329	-7.529	33.54	26.01	-41.07	206.01	138.93
24	-62.41	113.79	52.24	70	100	70	-61.3	28.74	-28.7	0	129.8	-17.8	80.7	80.71	-80.71	260.71	99.289	-7.791	31.83	24.04	-39.62	204.04	140.38
25	-70.34	114.83	51.03	70	100	70	-58.5	31.49	-31.5	0	134.7	-19	75.1	75.13	-75.13	255.13	104.87	-8.017	29.83	21.82	-37.85	201.82	142.15
26	-78.28	115.86	49.83	70	100	70	-56	34.04	-34	0	139.8	-20.2	68.8	68.82	-68.82	248.82	111.18	-8.209	27.52	19.31	-35.73	199.31	144.27
27	-86.21	116.9	48.62	70	100	70	-53.6	36.41	-36.4	0	145.2	-21.4	61.6	61.62	-61.62	241.62	118.38	-8.373	24.8	16.43	-33.18	196.43	146.82
28	-94.14	117.93	47.41	70	100	70	-51.4	38.6	-38.6	0	150.9	-22.6	53.2	53.23	-53.23	233.23	126.77	-8.513	21.56	13.05	-30.08	193.05	149.92
29	-102.1	118.97	46.21	70	100	70	-49.4	40.63	-40.6	0	156.8	-23.8	43	43.01	-43.01	223.01	136.99	-8.631	17.53	8.897	-26.16	188.9	153.84
30	-110	120	45	70	100	70	-47.5	42.51	-42.5	0	162.8	-25	29.2	29.17	-29.17	209.17	150.83	-8.731	11.95	3.223	-20.69	183.22	159.31