

Kinematic Analysis and Software Development of a Seven Degree of Freedom Inspection Robot

G. Shanmugasundar, R. Sivaramakrishnan, S. Venugopal

Abstract—Robots are booming as an essential substituent in the field of inspection. In hazardous environments like nuclear waste disposal, robots are really a necessitate one. In a view to meet such demands, this paper presents the seven degree of freedom articulated inspection robot. To design such a robot the kinematic analysis of seven Degree of freedom robot which can inspect the hazardous nuclear waste storage tanks is done. The effective utilization of universal joints for arms and screw jack mechanisms at the base gives the higher order of degree of freedom to the newly designed robot. The analytical method of deriving the manipulator forward as well as inverse kinematics is explained elaborately using the Denavit-Hartenberg Approach for the purpose of calculating the robot joints, links and end-effector parameters. The comparison of the geometric and the analytical approach is stated. The self-developed kinematic model gives the accurate positions of the end effector. The Graphical User Interface (GUI) is developed in Visual Basic language for the manipulation of kinematic results easily. This software gives the expected position of the end-effector accurately at short time compared to manual manipulations.

Keywords—Robot kinematics, screw jack mechanisms, Denavit-Hartenberg approach, universal joints.

I. INTRODUCTION

IN the current hi-tech world the application of robots has become the crucial role in industries. The exertions which were beyond the capacity of humans are now possible with robots. Particularly in the departments like inspections in nuclear industries, the safety and the accuracy created the demand for new robots. In nuclear power stations, many stainless steel canisters are used to store vitrified intermediate level wastes. These tanks are prone to defects at the weldments. These welds need to be inspected throughout their service life for signs of damage. A newly designed articulated robot with seven degree of freedom is proposed to carry out the inspection tasks.

The kinematic analysis gives the stability of the robot within the work space. Forward kinematics gives the position of end effector and the inverse kinematics gives the joint variables. In Visual Basic Language a special GUI named Robot Kinematics is created to do this kinematic analysis.

G. Shanmugasundar is Research Scholar in Department of Production Technology at Madras Institute of Technology, Anna University (Corresponding author: Mobile: 9941380398, e-mail: gshanmugasundar@gmail.com).

R. Sivaramakrishnan is Associate Professor in Department of Production Technology at Madras Institute of Technology, Anna University (e-mail: srk@mitindia.edu).

S. Venugopal is Head / Remote Handling, in Irradiation Experiments and Robotics Division, Indira Gandhi Centre for Atomic Research, India (e-mail: venu@igcar.gov.in).

II. BACKGROUND OF THE WORK

With the advances in technology, the demands for Inspection Robots are also greater than before. Researches continue to meet such demand. A review of similar researches is done to understand the recent trends in inspection technology [3], [5] and [6]. Formerly Bing L. Luk et al. have developed three climbing robots namely WIC, SADIE and Robug III, which were used for inspecting tile-walls of high-rise buildings, for carrying out ultrasonic inspection and surface preparation inside reactor cooling gas ducts and for working in unstructured environment respectively [9]. X.G. Fu et al. have introduced new auto-inspection robot system for weld inspection in nuclear pipes [13]. This system also performs trajectory planning, 3D simulation, auto-operation, ultrasonic signal analysis and 3D reconstruction according to the measured flow data.

Forward kinematics analysis of Scorbot Er Vplus is done by S. Navaneetha Santhakumar. The robot system is modeled using Lab view and the result validation is done using Robocell 3D graphic software [11]. Denavit Hartenberg approach is used to obtain the kinematic model of the robot. Elias Eliot et al. have presented five axes robot manipulator which is made up of commercially available kits [4]. The robot is quite similar to the Rhino XR-4. The design is done in Catia and Auto-Cad software. Kinematic analysis and work volume evaluation are also done. In the dangerous conditions like power transmission lines Gongping Wu et al. has developed double arm inspection robot [7]. Kinematics and dynamics simulation is performed based on virtual prototyping technology. Adams software is used in modeling and simulation research of inspection robot.

Baki Koyuncu et al. have made software development for the Lynx 6 Robot Arm [2]. The authors have done the forward and inverse kinematics solution with Denavit Hartenberg Conventions. Software named MSG is developed which is capable of testing the motional Characteristics of the robot. C Programming is implemented in developing the software with Visual Studio.Net 2005 Development Platform. This software is proposed to compute the Forward and inverse kinematics of the particular Lynx-6 Robot arm. Jayarajan., K. et al. have developed the telemanipulator in which a master slave arrangement is provided. This manipulator system is being successfully installed in BARC (Bhabha Atomic Research Centre) for Waste management Project Division. Its performed is evaluated for the intended tasks. Kinematic modeling and Maneuvering of five axes Articulated Robot Arm is done by T.C. Manjunath et al., in which the robot is designed entirely from indigenous components [10]. The

simple pick and place operation is performed within the workspace. A GUI is developed in C++ language which performs the manipulation works.

III. METHODOLOGY

The entire work described in this paper is divided into stages and is accomplished accordingly. The simple flowchart is shown in Fig. 1 which depicts the flow of this research work.

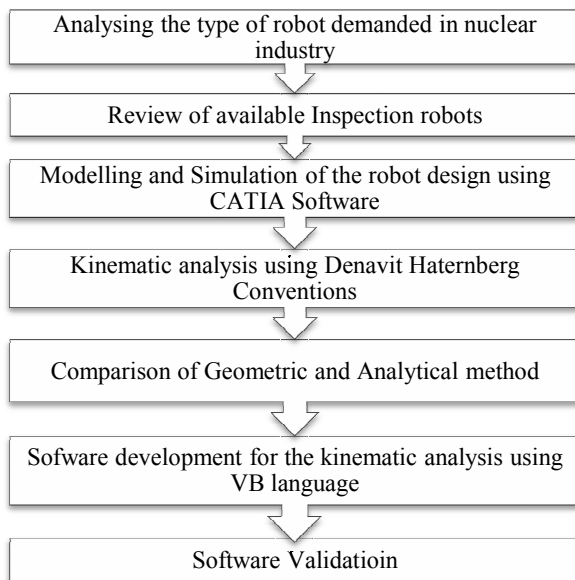


Fig. 1 Work Methodology

IV. ROBOT MODELING

The mechanical configuration of the robot is modeled using 3D modeling software CATIA as shown in Fig. 2. The effective utilization of the screw jack mechanism has been implemented for the base up and down movement of the manipulator. The arms of the robot have two universal joints for flexible movement of the arm which was utilized for maneuvering around the outer surface of the cylindrical steel canister. The robot manipulator comprises of totally seven degrees of freedom. They are given in Table I.

TABLE I
LIMITS OF THE ROBOT

S. No	Robot Element	Type of Motion	Limits (in degrees)
1	Base	Twist, T_1	-360 to 360
2	Screw jack	Prismatic, P_1	0 to 220 mm
3	Universal joint 1	Rotational	R_1 -90 to +60
			R_2 -90 to +60
4	Universal joint 2	Rotational	R_3 -60 to +90
			R_4 -60 to +90
5	Knuckle joint 1	Revolute R_5	-120 to +120

This robot configuration can be simply denoted as T-P-2R-2R-R configuration. The geometric structure of the robot is shown in Fig. 2, which denotes the dimensions of the entire

robot. The important components are labeled with their specifications.

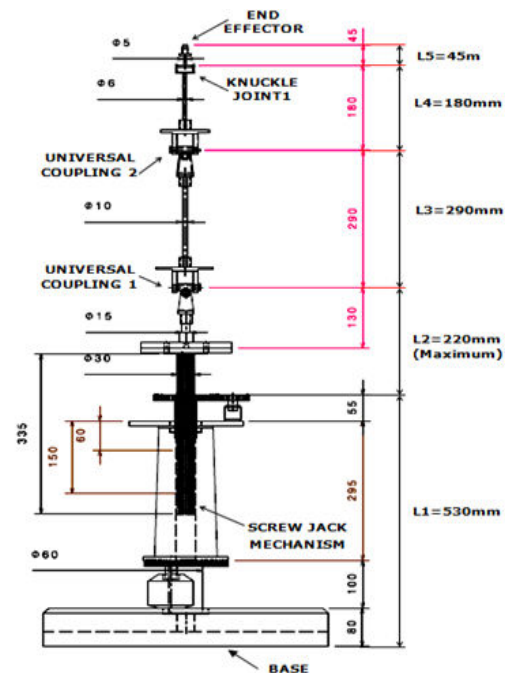


Fig. 2 Mechanical configuration of the robot

The components of the robot are designed and assembled in the CATIA software as shown in Fig. 3. The Degree of Freedom of the components is also specified in the Fig. 3.

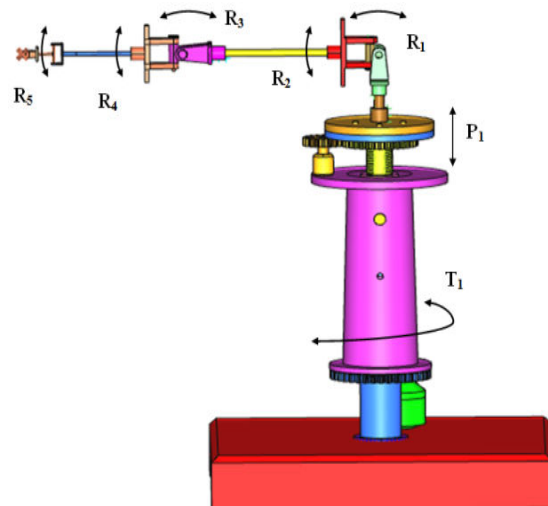


Fig. 3 Assembled view in CATIA software

V. KINEMATIC ANALYSIS

To demonstrate the robot's ability to perform an inspection purpose, its flexibility and locality must be verified. This is done with kinematic analysis. In this research work, the Denavit-Hartenberg's kinematic approach has been used for

modeling the proposed seven degree of freedom robot arm. Fig. 4 shows the Kinematic model of kinematics.

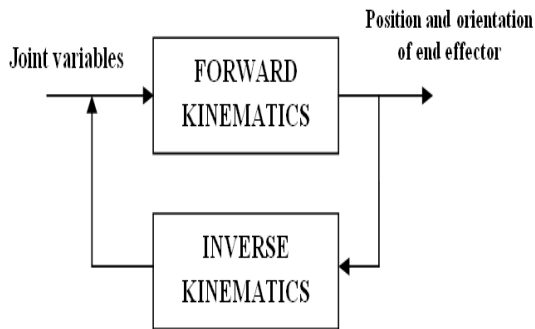


Fig. 4 Kinematic model

The representation of the axis of the joints is part coordinate system. To develop the part coordinate system the home position of the robot is used. In the home position the X axis and Z axis of the joint are expressed as per the convention of Denavit-Hartenberg's kinematic approach [12]. The movement of the joints is also depicted in the diagram for easy understanding. For kinematic analysis the Part co-ordinate system as shown in Fig. 5 is derived as per the convention of Denavit-Hartenberg's kinematic approach

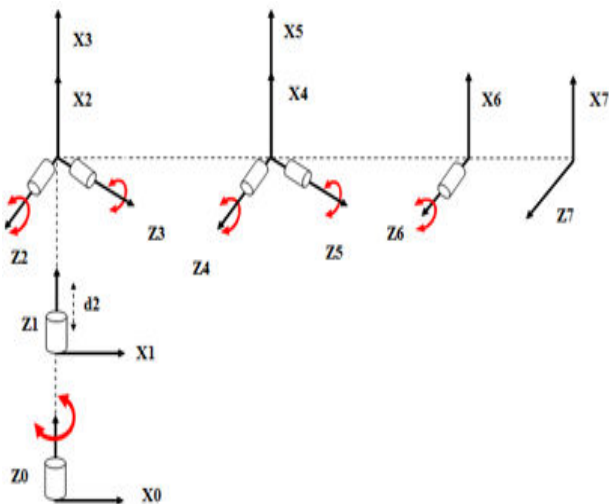


Fig. 5 Part co-ordinate system of the robot

VI. DIRECT KINEMATICS

Direct kinematics also referred as forward kinematics in which the link length and the angle of each joints of a manipulator are known and the position of end effector in the desired work volume of the robot is determined [1]. In this work forward kinematics is done by both geometric and analytical approach.

A. Geometric Approach

This is straightforward method of calculating the final position of end effector [8]. In this method the links are represented as 2-D lines. The angles are found with respect to

the reference axis. The geometric figure of the robot is shown in Fig. 6. In this analysis the joint angles θ_4 and θ_6 are considered to be zero.

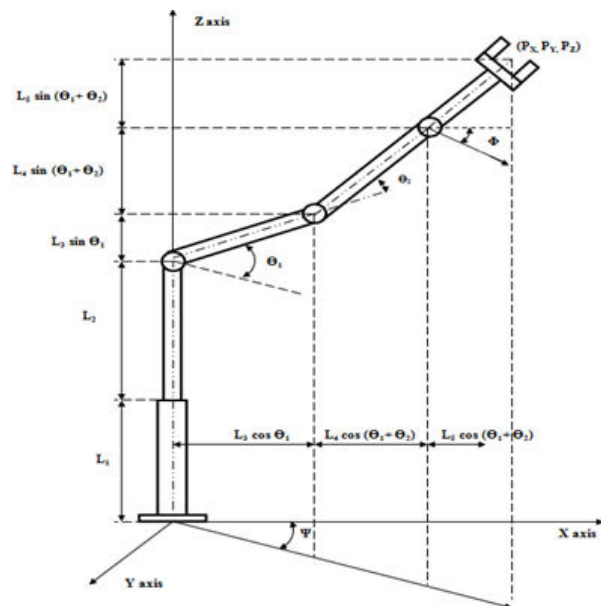


Fig. 6 Kinematic structure of the robot

The end positions are calculated by using the following derivations

$$P_x = (L_3 \cos \theta_1 + L_4 \cos (\theta_1 + \theta_2) + (L_5 \cos (\theta_1 + \theta_2) \times \cos \varphi)) \cos \psi \quad (1)$$

$$P_y = (L_3 \cos \theta_1 + L_4 \cos (\theta_1 + \theta_2) + (L_5 \cos (\theta_1 + \theta_2) \times \sin \varphi)) \sin \psi \quad (2)$$

$$P_z = L_1 + L_2 + L_3 \sin \theta_1 + L_4 \sin (\theta_1 + \theta_2) + L_5 \sin (\theta_1 + \theta_2) \quad (3)$$

The sample calculations are done and the results are tabulated in the Table II, which depicts the geometric calculation for three positions like home position, full extend and all angles at a constant angle.

TABLE II
TABULATION OF GEOMETRIC APPROACH

#	θ_1 Degree	θ_2 Degree	Φ Degree	Ψ Degree	End values mm	Observation
1.	0	0	0	0	515 0 750 0	Home position
2.	90	0	0	0	0 1265 312.31	Full extend
3.	30	30	30	30	176.19 1089.85	All angles at 30°

B. D-H Approach

This approach is complicated than the geometric approach. Denavit-Hartenberg's conventions are used in this approach.

By using the generalized final D-H matrix the following D-H parameter table is derived. The D-H parameters are clearly depicted in Table III. It denotes the four necessary parameters to be calculated for analytical approach.

TABLE III
D-H PARAMETER TABLE

#	α_i (degree)	a_i (mm)	d_i (mm)	θ_i (degree)
1	0	0	d_1	θ_1
2	90	0	d_2	0
3	90	0	0	θ_3
4	0	a_4	0	θ_4
5	-90	0	0	θ_5
6	0	a_6	0	θ_6
7	0	a_7	0	θ_7

Therefore the seven transformation matrices are formed as follows,

$$\begin{aligned}
 A_1 &= \begin{pmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad A_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
 A_3 &= \begin{pmatrix} C_3 & 0 & S_3 & 0 \\ S_3 & 0 & -C_3 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad A_4 = \begin{pmatrix} C_4 & -S_4 & 0 & C_4 a_4 \\ S_4 & C_4 & 0 & S_4 a_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
 A_5 &= \begin{pmatrix} C_5 & 0 & -S_5 & 0 \\ S_5 & 0 & C_5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad A_6 = \begin{pmatrix} C_6 & -S_6 & 0 & C_6 a_6 \\ S_6 & C_6 & 0 & S_6 a_6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
 A_7 &= \begin{pmatrix} C_7 & -S_7 & 0 & C_7 a_7 \\ S_7 & C_7 & 0 & S_7 a_7 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}
 \end{aligned}$$

The above derived transformation matrices are multiplied to attain the final transformation matrix which gives the position and orientation of the end effector

$$A_1 * A_2 * A_3 * A_4 * A_5 * A_6 * A_7 = {}^0T_7 \quad (4)$$

$${}^0T_7 = \begin{pmatrix} C_1(C_3C_{45}C_{67} - S_3S_{67}) & C_1(-C_3C_{45}S_{67} - S_3C_{67}) & -C_1C_3S_{45} + S_1C_{45} & (C_1C_3C_{45} + S_1S_{45})*(C_{67}a_7 + C_6a_6) \\ & -S_1S_{45}S_{67} & & -C_1S_3(S_{67}a_7 + S_6a_6) + (C_1C_3C_4 + S_1S_4)a_4 \\ S_1(C_3C_{45}C_{67} - S_3S_{67}) & S_1(-C_3C_{45}S_{67} - S_3C_{67}) & -S_1C_3S_{45} + C_1C_{45} & (S_1C_3C_{45} + C_1S_{45})*(C_{67}a_7 + C_6a_6) \\ & -C_1S_{45}C_{67} & -C_1S_{45}S_{67} & -S_1S_3(S_{67}a_7 + S_6a_6) + (S_1C_3C_4 + C_1S_4)a_4 \\ S_3C_{45}C_{67} + C_3S_{67} & -S_3C_{45}S_{67} + C_3C_{67} & -S_3S_{45} & S_3C_{45}(C_{67}a_7 + C_6a_6) + S_3C_4a_4 + C_3S_{67}a_7 \\ & & & + C_3S_6a_6 + d_2 + d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5)$$

This final transformation matrix gives the exact position and orientation of the end effector. The first 3x3 matrix denotes the orientation matrix and the 3x1 matrix on the right denotes the position matrix.

$$\begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \text{Orientation matrix} & \text{Position matrix} \end{pmatrix} \quad (6)$$

C. Forward Kinematics Solution by Analytical Approach:

The standard link lengths, the length of the prismatic link (d_2) and required angles are considered for calculation. The link lengths are $d_1=530\text{mm}$, $a_4=290\text{mm}$, $a_6=180\text{mm}$, $a_7=45\text{mm}$. The maximum lift is $d_2=240\text{mm}$ and the joint angles are $\theta_1, \theta_3, \theta_5, \theta_7$ be 30° and $\theta_2, \theta_4, \theta_6$ be 0°

$$P_x = (C_1 C_3 C_{45} + S_1 S_{45}) * (C_{67} a_7 + C_6 a_6) - C_1 S_3 (S_{67} a_7 + S_6 a_6) + (C_1 C_3 C_4 + S_1 S_4) a_4 \quad (7)$$

$$= 404.726 \text{ mm}$$

$$P_y = (S_1 C_3 C_{45} + C_1 S_{45}) * (C_{67} a_7 + C_6 a_6) - S_1 S_3 (S_{67} a_7 + S_6 a_6) + (S_1 C_3 C_4 + C_1 S_4) a_4 \quad (8)$$

$$= 107.246 \text{ mm}$$

$$P_z = S_3 C_{45} (C_{67} a_7 + C_6 a_6) + S_3 C_4 a_4 + C_3 S_{67} a_7 + C_3 S_6 a_6 + d_2 + d_1 \quad (9)$$

$$= 1009.303 \text{ mm}$$

Similarly the orientation elements are computed and tabulated as shown in the Table IV. These Orientation and position elements are needed for inverse kinematics.

TABLE IV
ORIENTATION ELEMENTS

$n_x = 0.56$	$o_x = -0.82$	$a_x = 0.06$
$n_y = -0.18$	$o_y = -0.19$	$a_y = -0.97$
$n_z = 0.81$	$o_z = 0.53$	$a_z = -0.25$

D. Comparison of Geometrical and Analytical Approach

The comparison of the results generated by geometrical and algebraic method shows that there is a minor deviation. The end result of both approaches is tabulated in Table V.

TABLE V
COMPARISON OF GEOMETRIC AND ALGEBRAIC APPROACH

#		Trail 1 Degree	Trail 2 Degree	Trail 3 Degree
θ_1		30	20	10
θ_2		0	0	0
θ_3		30	20	10
θ_4		0	0	0
θ_5		30	20	10
θ_6		0	0	0
θ_7		30	20	10
By geometrical Method (mm)	P_x	310.15	412.49	484.21
	P_y	174.95	143.09	79.42
	P_z	1285.53	1190.60	1075.60
By algebraic method (mm)	P_x	404.69	460.67	504
	P_y	107.246	80.13	41.3
	P_z	1009.303	1073.87	845.23

The positions of the End Effector depend upon the various joint angles. Due to the changes in the individual joint angles the End-effector position is varied. This variation is denoted in the graph by varying the individual angles and keeping the other angles constant to zero.

The Base twist angle is varied by keeping the other six angles as zero; the graph as shown in Fig. 7 is obtained

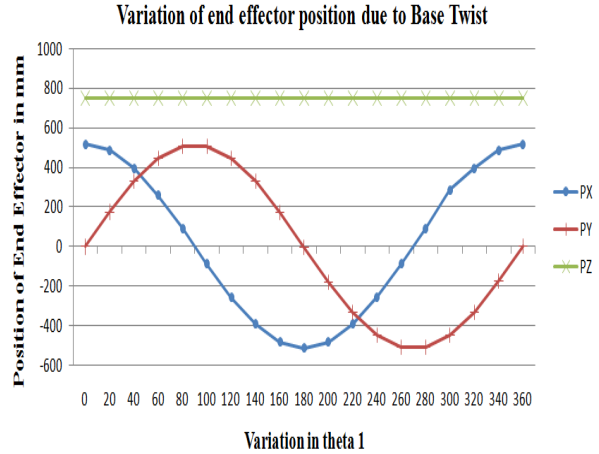


Fig. 7 End Effector Variations - Trail 1

Similarly the next angles are also varied considering the remaining angles to be constant. The theta six is varied by considering other angles to be zero; the graph shown in the Fig. 8 is obtained.

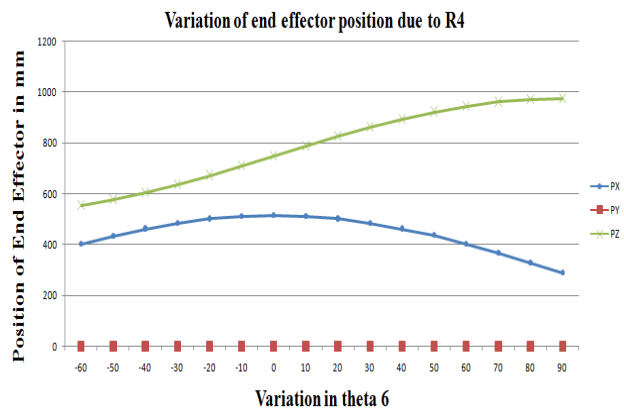


Fig. 8 End Effector Variation - Trial 2

By obtaining the graphs for all the variables, it can be inferred that P_z remains unchanged by varying the theta 1, theta 4 and theta 5. The position of P_y remains unchanged by varying theta 3, theta 6 and theta 7. The position P_x varies by varying any of the joint variables.

VII. INVERSE KINEMATICS

In inverse kinematics the link length and the position of end effector are known and angle of each joint is calculated. There will be coupled angles formed in forward kinematics. To decouple the angles, the ${}^R T_H$ matrix should be routinely pre-multiply with the individual A_n^{-1} matrices. This will yield to find the individual angles of the links.

$${}^R T_H = \begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} = A_1 * A_2 * A_3 * A_4 * A_5 * A_6 * A_7 \quad (10)$$

Pre-multiply the matrices by its inverses. Start with A_1^{-1}

$$A_1^{-1} \times \begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} = A_2 * A_3 * A_4 * A_5 * A_6 * A_7 \quad (11)$$

Pre-multiply the transformation matrix with $A_1^{-1} A_2^{-1}$ and A_3^{-1}

$$A_3^{-1} A_2^{-1} A_1^{-1} \times \begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} = A_4 * A_5 * A_6 * A_7 \quad (12)$$

By equating the above matrices, the individual angles are obtained

$$\theta_1 = 2 \times A \tan 2(p_y, p_x) \quad (13)$$

$$\theta_2 = 0$$

$$\theta_3 = \pm A \tan 2\left(-a_z / \sin_{45}, \sqrt{1 - (-a_z / \sin_{45})^2}\right) \quad (14)$$

$$\theta_4 = \pm A \tan 2(S_4, C_4) \quad (15)$$

$$S_4 = (S_1 * p_x - C_1 * p_y - S_{45} * C_{67} * a_7 - S_{45} * C_6 * a_6) / a_4$$

$$C_4 = \sqrt{1 - ((S_1 * p_x - C_1 * p_y - S_{45} * C_{67} * a_7 - S_{45} * C_6 * a_6) / a_4)^2}$$

$$\theta_5 = \theta_{45} - \theta_4 \quad (16)$$

$$\theta_6 = \pm A \tan 2(S_6, C_6) \quad (17)$$

$$S_6 = (-S_3 * C_1 * p_x - S_3 * S_1 * p_y + C_3 * p_z - C_3(d_2 + d_1) - S_{67} * a_7) / a_6$$

$$C_6 = \sqrt{1 - ((-S_3 * C_1 * p_x - S_3 * S_1 * p_y + C_3 * p_z - C_3(d_2 + d_1) - S_{67} * a_7) / a_6)^2}$$

$$\theta_7 = \theta_{67} - \theta_6 \quad (18)$$

A. Evaluation of Inverse Kinematics

The end effector position formed by joint angles used in the preceding section is taken as inputs. The standard link lengths, the final position and the orientation of the robot are taken as shown in the Table VI. By using the expressions given above,

the angles are computed and tabulated in the Table VI. The final angles obtained from the inverse kinematics approach are found similar to the inputs given in the forward kinematics, which is the expected result.

TABLE VI
THE FINAL VALUES OBTAINED

θ_1	30.088
θ_2	0
θ_3	30.39
θ_4	0.29
θ_5	29.32
θ_6	2.00
θ_7	25.94

VIII. SOFTWARE DEVELOPMENT

Now-a-days softwares play the vital role in validation of various fields. They make complex manipulations easy and quick. The software results are also verified with the manual calculation. Moreover they are helpful in further kinematic analysis. The software must be in the way to perform both forward as well as inverse kinematics. For forward kinematics, the height of lift and the angles of the corresponding joints are to be acquired as input parameters and the result is to produce the position of the end effector. For inverse kinematics, the vice versa of the above along with the orientation matrix

The GUI is made in such a way that it describes the robot parameters in detail. Clearly figured part coordination system is shown, which describes the Z-axis and X-axis vectors of the joints. The definition of the parameters is displayed for easy understanding. The final solution matrix is also exhibited. Then in the next tab the required parameters are given as input. In spite of position matrix, the provision is there to get the final orientation matrix. This feature differentiates this from the previously available softwares. These values are used in the calculation of the inverse kinematics. Fig. 9 shows the Algorithm for the software development. This algorithm is developed in such a way it gives choices from the user to select between the forward and inverse mode.

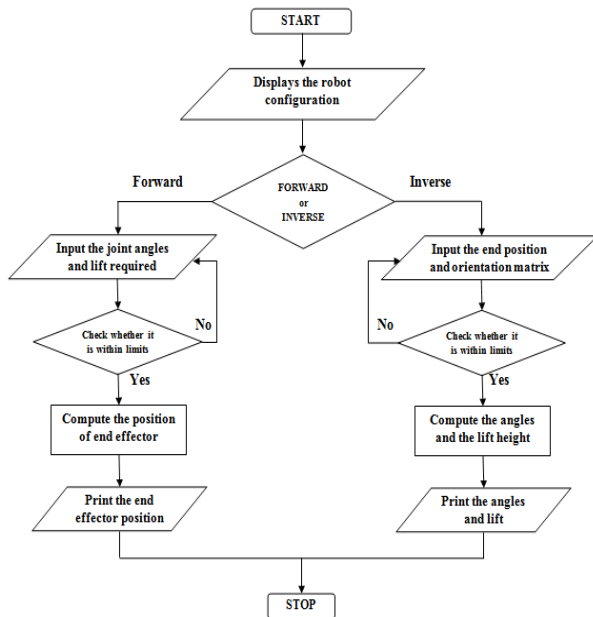


Fig. 9 Software Algorithm

The software for kinematic solution of this robot is developed by using Visual Basic development Platform. The Graphical User Interface (GUI) of the software package is shown in Figs. 10-12. The software results are compared with the manual calculation and the software is successfully validated.

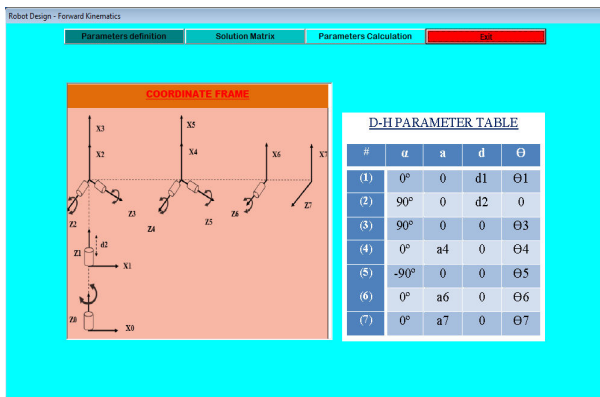


Fig. 10 Front panel



Fig. 11 Data panel

For the Trail 1 as shown in Table IV the values calculated from the software. It is compared with the manual calculation and found to be similar. Thus the software developed gives the position and orientation of the end effector as shown in Fig. 12.

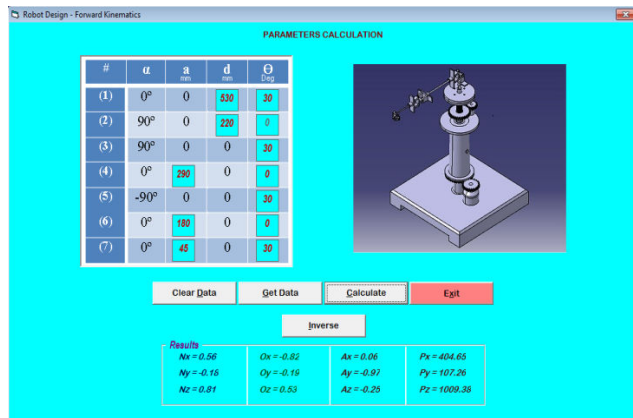


Fig. 12 GUI showing the final results

TABLE VII
COMPARISON OF SOFTWARE RESULTS WITH ANALYTICAL VALUES

S.No	Analytical solution	Software solution	Error percentage
1	$P_x = 404.726 \text{ mm}$	$P_x = 404.65 \text{ mm}$	0.076
2	$P_y = 107.246 \text{ mm}$	$P_y = 107.26 \text{ mm}$	0.014
3	$P_z = 1009.30 \text{ mm}$	$P_z = 1009.38 \text{ mm}$	0.080

From the above comparison Table VII, it can be conferred that the software value and the manual calculation values are found to be correct. The little deviation in the values is expressed as error. The error percentage is found in the negligible range.

IX. CONCLUSION AND FUTURE WORK

Thus in this paper the kinematics and software development is well explained. The uniqueness of the seven DOF robots, its flexibility and ability of positioning is demonstrated. The designed robot with seven degree of freedom robot suggested in this paper is theoretically stable to identify the weld defect in the steel waste vault storage tanks in nuclear power plants

in future. The Denavit-Hartenberg (D-H) approach has been successfully used for modeling the robot links and joints in this work. The comparison of the forward kinematics by kinematic and algebraic approach is done. The inverse kinematics approach is clearly explained. The unique software for manipulating the forward and inverse kinematics is the best part of this work. The dynamic analysis is proposed to be done in future.

As the researches continue in the world there will be increased demand for robots in future. Due to decline of non-renewable resources, the world has to rely on the nuclear technology for the power source. This scenario leads to construction of more nuclear power station stations, meanwhile the need for the inspection and maintenance of the stations also raise. There will a demand for more economical and flexible robot system, which can perform all the inspections activities of the nuclear power stations and make the nuclear power source to be a safer means of power generation. To conclude the newly developed robot system developed now are going to have a great demand in the near future.

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REFERENCES

- [1] Anurag Verma, Mehul Gor. "Forward Kinematics Analysis of 6-DOF arc welding robot", *International Journal of Engineering Science and Technology*, Vol. 2(9), 2010, 4682-4686
- [2] Baki Koyuncu, Mehmet Guzel, "Software development for the kinematic analysis of a Lynx 6 Robot Arm", *World Academy of Science, Engineering and Technology*, vol.30, August 2007, pp. 252-257.
- [3] Clyde R. Ward, W. Ivan Lewis, Robert F. Fogle, Paul S. Hebert, Phillip J. French, and Frank M. Heckendorn. *Robotics Applications at the Savannah River Site* in: WSRC-MS-2000-00061
- [4] Elias Eliot, B.B.V.LDeepak, D.R.Parhi., and J.Srinivas, "Design& Kinematic Analysis of an Articulated Robotic Manipulator", *ICMIE 2012*.
- [5] Fei Yanqiong, Song Libo. "Design and Analysis of Modular Mobile Robot with Magnetic Wheels" in: *WSEAS Transactions on Applied and Theoretical Mechanics* ISSN: 1991-8747 902 Issue 12, Volume 3, 2008
- [6] Gabriel Munteanu, "Analysis of the accuracy parameters for the Articulated arm industrial robot using Modern instruments and software" *U.P.B. Sci. Bull., series d*, vol. 72, ISS. 4, 2010 ISSN 1454-2358
- [7] Gongping Wu, Xiaohui Xiao, E Du., L.Sanping. "Kinematics and dynamics simulation of inspection Robot for power transmission line", *Proceedings of the 5th WSEAS Int. Conf On signal processing, robotics and automation*, Madrid, Spain, February 15-17, 2006 (pp70-76)
- [8] John J. Craig. *Introduction To Robotics Mechanics and Control*, pp 109-114, Prentice Hall. 2005
- [9] B.L. Luk, A.A.Collie, D.S.Cooke, and S. Chen. "Walking and Climbing Service Robots for Safety Inspection of Nuclear Reactor Pressure Vessels", 2005
- [10] Manjunath.T.C. "Kinematic modelling and manoeuvring of a 5 axes articulated robot arm", *World academy of science, engineering and technology* 2007.
- [11] S. Navaneethasanthakumar, K. M. Mohanasundaram, N. Godwin Raja Ebenezer, C. Krishnaraj (2012), "Forward Kinematics Analysis of SCORBOT ER V Plus using LabVIEW", *European Journal of Scientific Research* ISSN 1450-216X Vol.72 No.4 (2012), pp. 549-557
- [12] Saeed B.Niku. *Introduction To Robotics*, pp 67-76, Prentice Hall. 2001
- [13] X.G. Fu, G.Z. Yan, B. Yan, H. Liu. A new robot system for auto-inspection of intersected welds of pipes used in nuclear power stations in: Springer-verlag London Limited 2005.



G. Shanmugasundar is currently pursuing Ph.D in the area of Inspection robot in Madras Institute of Technology, Anna University, Chennai, Tamil Nadu, India. His research work includes the kinematic study, modeling and simulation and its application in nuclear industry. He is also working as Assistant Professor in the department of Mechanical Engineering at GKM College of Engineering & Technology, Affiliated to Anna University Chennai. He obtained his Bachelor's degree in Mechanical Engineering from AVC Engineering College, Mailaduthurai. He has a vast experience in teaching CAD/CAM, modern manufacturing systems, Special casting process, Manufacturing Technology, Mechatronics, Engineering Graphics, and Design Subjects. He has written a book on Computer Aided Manufacturing. He has specialization in the areas of high end softwares. He is contributing as a life member with ISTE, CMTI and Indian Science Congress in their activities.



Machining Work.

Dr. R. Sivaramakrishnan received his M.E degree in Production Engineering and Ph.D in the field of Parallel manipulators from the Madras Institute of Technology, Anna University, Tamil Nadu, India. His research background is also Parallel Manipulator, which includes the Tripod, and the Triglide manipulator, Parallel Mechanism Design, surface grinding and its application for



Dr. S. Venugopal is the head of Remote Handling, Irradiation Experiments and Robotics Division (RIRD) at Indira Gandhi Centre for Atomic Research, Kalpakkam-603102 Tamilnadu India.