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Design and Analysis of a newly developed Seven Degree of Freedom Robot for Inspection

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ABSTRACT

With the advances in technology humans created the robots for their comfort and difficult jobs. Now the current scenario is that they are indispensable in some areas like nuclear inspections. To accomplish their specified works they must be developed with more precision components to survive in unstructured conditions. The most important process in the development of robots is the selection and design of the components for building up of the robot. This paper gives the overview of the selection and design of the components and the forward kinematics of the robot. The analytical method of deriving the manipulator's forward kinematics is explained elaborately using the Denavit-Hartenberg Approach for the purpose of calculating the robot joints, links and end-effectors parameters.

Key words: Degree of Freedom robot, Inspection robots, Screw jack mechanism, Deflection, Bending moment

1. INTRODUCTION

Robotics is a special engineering science which deals with the designing, modeling, implementation and application of robots. Building up new robot was a hard task in the initial development of robotics. There were some rules to be followed very strictly in concern to create a new robot. Any robot should not harm human being, it should obey human being and it should protect itself from harm. But now-a-days, it has become simple due to advanced technology in real time simulation with a use of advanced software's. This software's reduced the risks in development process. Some of the previously done works are as follows. K. Jayarajan et al. have developed the tele manipulator in which a master slave arrangement is provided [1]. The master is assembled in a non-hazardous area. The slave is made to work in the unstructured environment. The slave would exactly reproduce the motions performed by the master in the remote locations. This manipulator system is being successfully installed in BARC (Bhabha Atomic Research Centre) for Waste management Project Division.

X.G. Fu et al. have introduced his new auto-inspection robot system for weld inspection in nuclear pipes [2]. Robot system consists of half clamp as mounting unit and a half base as circumferential rotational joints, an arm, a controller and an IPC unit. The system is re-constructible by adjusting the size of the arm to adapt to the different working conditions. In the nuclear power stations at Savannah River Site (SRS), Clyde R. Ward et al. has developed new four robotics technology from the existing systems [3]. Their works are mobile robots, a pipe crawler, special manipulators, and custom-designed tooling. The author's motive is to reduce the radiation exposure to the working personnel.

In the dangerous conditions like power transmission lines Gongping Wu et al. has developed double arm inspection robot. Kinematics and dynamics simulation is performed based on virtual prototyping technology [4]. UG three dimensional solid modeling function and Adams software is used in modeling

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and simulation research of inspection robot. This work is applied for inspection purposes in the 220kv overhead high-voltage transmission lines. M. H. Korayem et al, have designed and modeled a 6R robot for which experimental analysis is also done [5]. The authors have developed the robot in such a way that each joint is controlled by an independent DC Actuator. The kinematic and dynamic analysis is done by Denavit Hartenberg conventions and verified using MATLAB and ADAMS software. Gabriel Munteanu et al, has analyzed the Accuracy Parameters for the Articulated Arm Industrial Robot using Modern Instruments and Software [6]. The chains and mechanisms of the 5R robotic structure are considered for which accuracy analysis and frequency analysis is done. Choong W. H. and Yeo K. B have developed a 3DOF robot in which the structural design of the lower arm is studied through Computer Aided Engineering [7]. The basics of the robotic components are studied to develop the new inspection robot for nuclear environments [8-12].

2. SELECTION OF COMPONENTS

The newly designed inspection robot mainly consists of two sections viz. Base and the Arm. The base of the robot comprises of lifting mechanism. The arm carries the inspecting sensors. The essential components of robot are,

1. *Base*: for stable fixing
2. *Screw jack mechanism*: for lifting purpose
3. *Arms*: for extending the reach of end effectors
4. *Universal Coupling*: for maximum flexibility
5. *End Effectors*: to hold the inspection sensor

The important notable component of this robot is its lifting mechanism and double universal joint. Mild steel is used for developing the components of the robot. The robot system must be designed to bear the load exerted on it. The design of lifting mechanisms and the design of coupling are considered important from design point of view. The Base, Arms and End Effector are designed as per the design of screw jack and universal coupling.

2.1. Design of lifting mechanism

Compared to the different lifting mechanisms screw jack mechanisms is found to well suited for the inspection tasks in those hazardous environment. A survey of lifting mechanisms is done and due to some of the disadvantages in them they are neglected. The rack and pinion method could not withstand the expected load. The telescopic mechanisms also fail to operate in heavy load condition. The chain mechanism gives more flexibility but more expensive and very complexity in controlling. Thus the screw jack mechanism in selected as it can withstand the load and simple to operate and moreover it is economical when compared to other methods.

2.2. Design criteria for screw jack

For designing the new screw jack for a specified purpose there is a need to analyze the stability of the design through theoretical calculation. These are lifting devices and should be capable to lift the desired load. So the input variable for designing the screw jack is the load applied, material used and their properties. Design of screw jack is done as follows;

2.2.1. Design of screw for spindle

Consider the outer diameter of the spindle as 30mm.

For the spindle of diameter 30mm the pitch should be 6mm. To find mean diameter, d which is the mean diameter of the core and outer diameter

$$d_0 = 30 \text{ mm and } p = 6$$

$$d = d_0 - \frac{p}{2} = 27 \text{ mm} \tag{1}$$

Therefore mean diameter d = 27 mm

To find the core diameter of the screw spindle, mean and outer diameter values are needed

$$d = (d_0 - d_c)/2 \tag{2}$$

$$d_c = 24 \text{ mm}$$

Then the torque required to rotate the screw in the nut has to be found

$$T = P \times \frac{d}{2} \tag{3}$$

Therefore by substituting tan $\alpha = 0.070$, tan $\varphi = 0.25$ values and the load 490 N, P value is found as 159.59 N Substituting the P value and mean diameter value in the torque equation, torque value is obtained

$$T = P \times \frac{d}{2} = 2154.5 \text{ N- mm} \tag{4}$$

$$= 2.15 \text{ N-m}$$

2.2.2. Design of the nut

The design of the nut should be suitable to fit the screw spindle for the easy lifting process. The suitable bearing pressure is incorporated between the screw and nut as $P_b = 18$ N

Considering the number of teeth in the nut to be 15

Height = (n × p) = 90 mm

2.2.3. Design of the outer casing

By considering the diameters of the spindle and nut, the diameter of the casing is designed as if it hosts the lifting mechanism. The base with little larger diameter as 150 mm and tubular stem to be 98 mm isselected.

2.3. Stress calculations

The robot system must be capable to bear the stress applied by the loads upon it. The calculated stress should be less than the maximum stress for the safer designs.

Compressive stress due to axial load:

$$\text{Load, } W = 490 \text{ N}, d_c = 24\text{mm}$$

$$\theta_c = W/A_c = 1.083 \text{ N/mm}^2 \tag{5}$$

Shear stress due to torque:

$$\tau = (16T_1/\pi d_c^3) = 0.793 \text{ N/mm}^2 \tag{6}$$

Maximum principal stress:

$$\theta_c(\max) = \frac{1}{2}\left[\theta_c + \sqrt{\theta c^2 + 4\tau^2}\right] = 1.5017 N/mm^2 \tag{7}$$

Maximum shear stress:

$$\tau_{(max)} = \frac{1}{2}\left[\sqrt{\theta c^2 + 4\tau^2}\right] = 0.96N/mm^2 \tag{8}$$

The maximum stress are much below the limits, therefore the design is safe.

2.4. Design of flexible coupling

To make the robot flexible some of the joint components should be used. By analyzing the available joints, the universal joint is selected for our robot. Universal joint consists of two degree of freedom it gives more flexibility to the robots. Two universal joints have been installed for better flexibility. The design calculations for the joint is as follows,

Design of universal joint consists of design of both shaft and pin.

2.4.1. Design of shaft

To design the shaft one should find the diameter of the shaft. The diameter should be designed in such a way to bear the torque transmitted. Assume the 50kg (490 N) to be applied, and then the torque transmitted is found as follows

Torque transmitted = force x distance between point of load to axis of joint

$$\mathrm{T} = \mathrm{F} \times \text{perpendicular distance} \tag{9}$$

$$= 490 \times (290 + 180 + 45)$$

$$\mathrm{T} = 0.252 \times 10^6 \text{ N-mm}^2$$

$$T = \frac{\pi}{16} \times \tau \times d^3 \tag{10}$$

The shear stress of the shaft material is considered to be τ = 60 MPa, which is equal to 60 N/mm^2 and d = 27.759 mm

2.4.2. Design of the pin

The pin is designed to withstand the load exerted by the shaft. The diameter of the pin should be suitably designed to withstand the stress. Since the pin experiences the double shear stress, therefore the torque transmitted will be

$$\mathrm{T} = 2 \times \frac{\pi}{4} \times d_p^{\,2} \times \tau_1 \times d \tag{11}$$

By substituting the known values, the d_p is found, d_p= 14.36 mm

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 eight degrees of freedom. They are

- Base twist (T)
- Base lift (P)
- Arm 1 – two rotational motions (2R)
- Arm 2 – two rotational motions (2R)

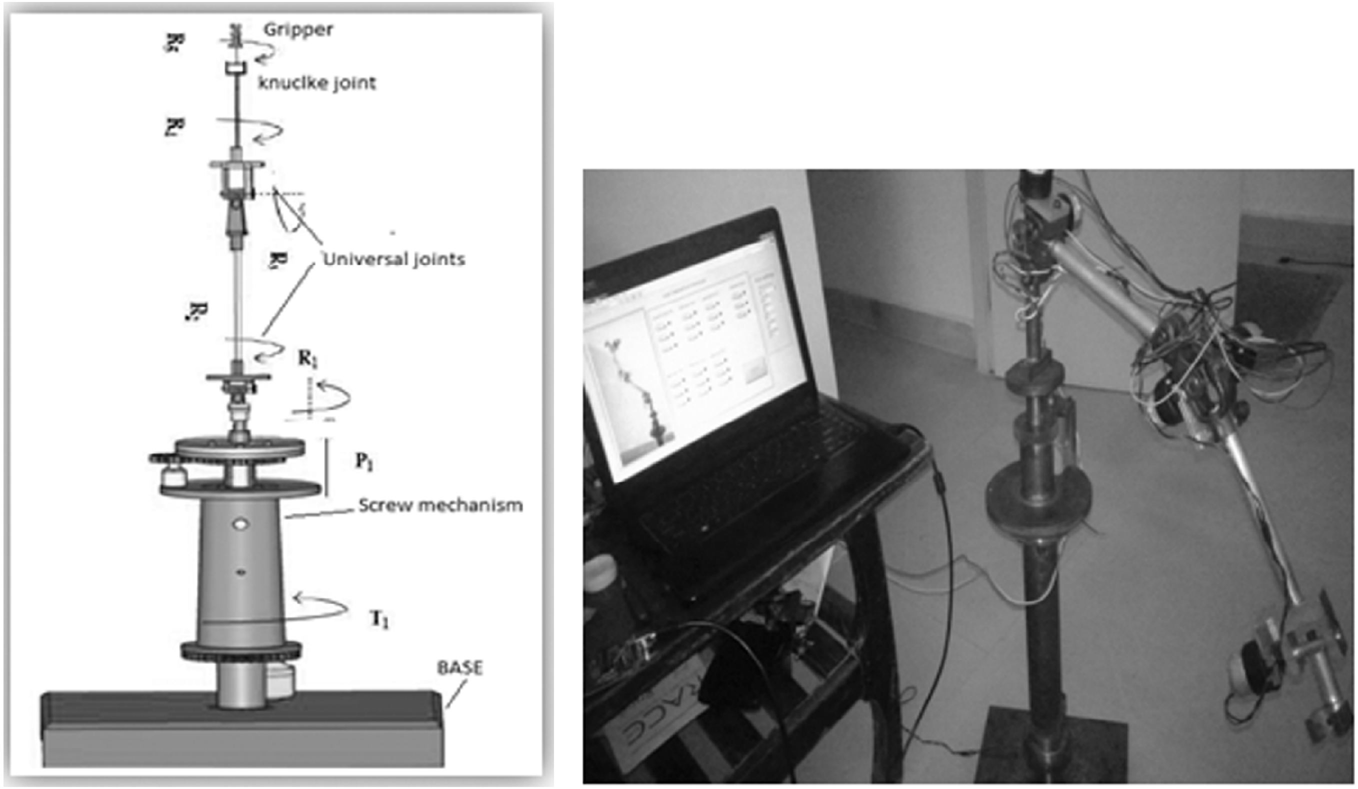

Figure 1: Overall view of the designed robot

- Arm 3 – two rotational motions (R)
- End effector revolute motion (R)

This is simply denoted as T-P-2R-2R-R-R configuration.

3. JOINT RANGE

The joints are expected to move in the certain range as shown in Table 1. Within this range the links are free to move without frictional resistance. Depending upon the assembly of the components the ranges are specified.

4. KINEMATIC ANALYSES

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

Table 1
Joint Ranges

Joint angle	*Range (in degrees)*
θ_1	-360 to + 360
$\theta_2 = 0$, d	0 to 240 mm
θ_3	-90 to + 60
θ_4	-90 to + 60
θ_5	-60 to + 90
θ_6	-60 to + 90
θ_7	-120 to + 120
θ_8	-180 to + 180

approach has been used for modeling the proposed eight degree of freedom robot arm. The simple Kinematic model is shown in the Figure 4, which depicts the input and output parameters of the kinematics.

4.1. Part coordinate system

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. 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 Figure 2 is derived as per the convention of Denavit-Hartenberg's kinematic approach

4.2. 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. In this work forward kinematics is done by both geometric and analytical approach.

4.3. Geometric Approach

This is straightforward method of calculating the final position of end effector. 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 Figure 3. In this figure the joint angles θ4 and θ6 are considered to be zero.

The end positions are calculated by using the following derivations

$$P_x = (L_3 \cos\theta_1 + L_4 \cos(\theta_1 + \theta_2) + (L_5 \cos(\theta_1 + \theta_2) \times \cos\theta) + (L_6 \cos(\theta_1 + \theta_2) \times \cos\alpha)) \cos\Psi$$
$$P_y = (L_3 \cos\theta_1 + L_4 \cos(\theta_1 + \theta_2) + (L_5 \cos(\theta_1 + \theta_2) \times \sin\theta) + (L_6 \cos(\theta_1 + \theta_2) \times \sin\alpha)) \sin\Psi$$
$$P_z = L_1 + L_2 + L_3 \sin\theta_1 + L_4 \sin(\theta_1 + \theta_2) + L_5 \sin(\theta_1 + \theta_2) + L_6 \sin(\theta_1 + \theta_2)$$

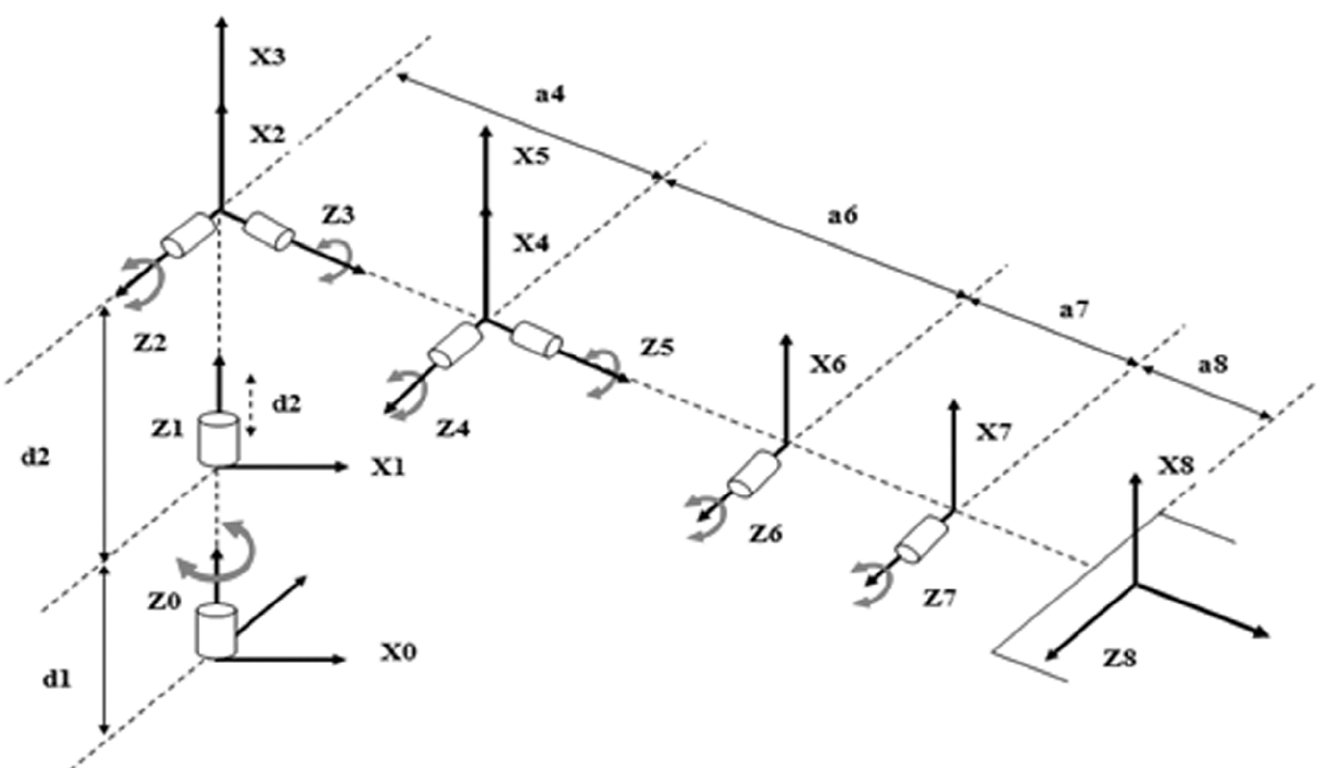

Figure 2: Part co-ordinate system of the robot

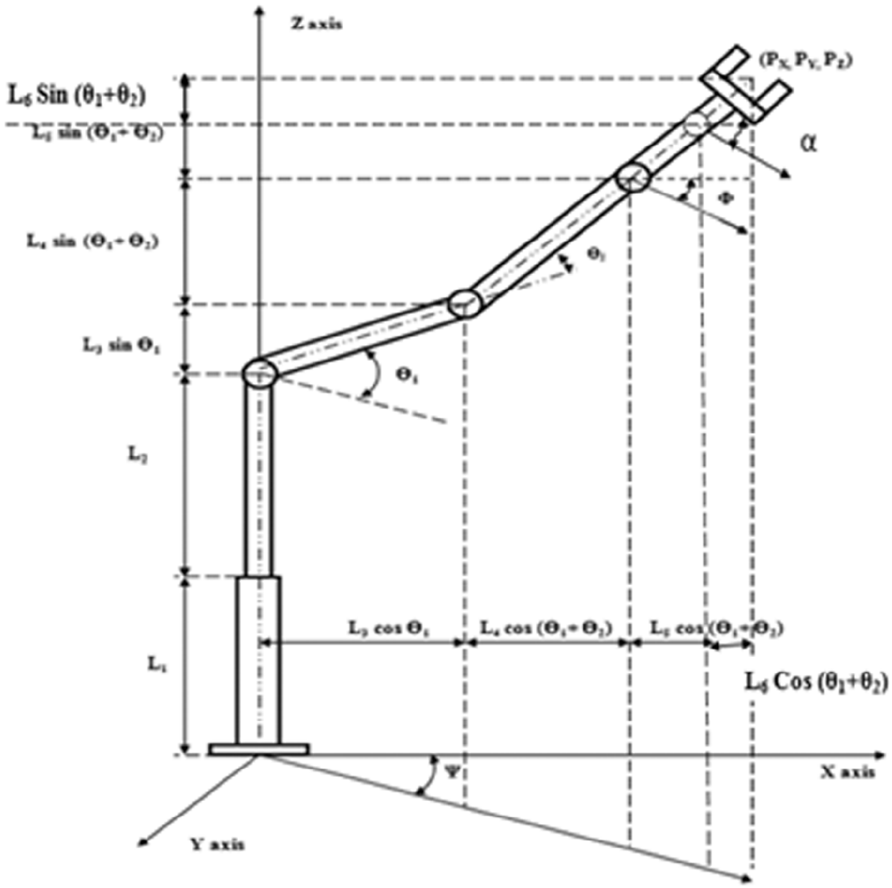

Figure 3: Geometric structure of the robot

4.4. 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 the Table 2. It denotes the four necessary parameters to be calculated for analytical approach.

Therefore eight matrices are formed as given below There are eight degrees of freedom. They are (T P 6R)

Therefore there are eight matrices formed, they are

Table 2
D-H Parameter Table

#	α	a	d	θ
(1)	0º	0	d1	θ1
(2)	90º	0	d2	0
(3)	90º	0	0	θ3
(4)	0º	a4	0	θ4
(5)	-90º	0	0	θ5
(6)	0º	a6	0	θ6
(7)	0º	a7	0	θ7
(8)	0º	a8	0	θ8

$$A1=\begin{pmatrix} C1 & -S1 & 0 & 0 \\ S1 & C1 & 0 & 0 \\ 0 & 0 & 1 & d1 \\ 0 & 0 & 0 & 1 \end{pmatrix} A2=\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & d2 \\ 0 & 0 & 0 & 1 \end{pmatrix} A3=\begin{pmatrix} C3 & 0 & S3 & 0 \\ S3 & 0 & -C3 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A4=\begin{pmatrix} C4 & -S4 & 0 & C4a4 \\ S4 & C4 & 0 & S4a4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} A5=\begin{pmatrix} C5 & 0 & -S5 & 0 \\ S5 & 0 & C5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} A6=\begin{pmatrix} C6 & -S6 & 0 & C6a6 \\ S6 & C6 & 0 & S6a6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A7=\begin{pmatrix} C7 & -S7 & 0 & C7a7 \\ S7 & C7 & 0 & S7a7 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} A8=\begin{pmatrix} C8 & -S8 & 0 & C8a8 \\ S8 & C8 & 0 & S8a8 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The matrix multiplications are done as follows

$$A1A2A3A4A5A6A7A8=\begin{pmatrix}
\begin{array}{c} c1c8(c3c45c67) \\ +s1s45c67c8 \\ +c1s8(-c3c45s67-s3c67) \\ -s1s45s67s8 \end{array} & \begin{array}{c} -c1s8(c3c45c67-s3s67) \\ -s1s45c67s8 \\ c1c8(-c3c45s67-s3c67) \\ -s1s45s67c8 \end{array} & \begin{array}{c} -c1c3s45 \\ +s1c45 \end{array} & \begin{array}{c} c1c8a8(c3c45c67-s3s67)+s1s45c67c8a8 \\ c1s8a8(-c3c45s67-s3c67)-s1s45s67s8a8 \\ +(c1c3c45+s1s45)(c67a7+c6a6) \\ -c1s3(s67a7+s6a6) \\ +(c1c3c4+s1s4)a4 \end{array} \\
\begin{array}{c} s1c8(c3c45c67-s3s67) \\ -c1s45c67c8 \\ s1s8(-c3c45s67-s3c67) \\ +c1s45s67s8 \end{array} & \begin{array}{c} -s1s8(c3c45c67-s3s67) \\ +c1s45c67s8 \\ s1c8(-c3c45s67-s3c67) \\ +c1s45s67c8 \end{array} & \begin{array}{c} -s1c3s45 \\ -c1c45 \end{array} & \begin{array}{c} s1c8a8(c3c45c67-s3s67)-c1s45c67c8a8 \\ s1s8a8(-c3c45s67-s3c67)+c1s45s67s8a8 \\ (s1c3c45-c1s45)(c67a7+c6a6) \\ -s1s3(s67a7+s6a6) \\ +(s1c3c4-c1s4)a4 \end{array} \\
\begin{array}{c} s3c45c67c8+c3s67c8 \\ -s3c45s67s8+c3c67s8 \end{array} & \begin{array}{c} -s3c45c67s8-c3s67s8 \\ -s3c45s67c8+c3c67c8 \end{array} & -s3s45 & \begin{array}{c} s3c45c67c8a8+c3s67c8a8-s3c45s67s8a8+c3c67s8a8 \\ s3c45(c67a7+c6a6) \\ +s3c4a4+c3s67a7+c3s6a6+d2+d1 \end{array} \\
0 & 0 & 0 & 1
\end{pmatrix}$$

5. CONCLUSION

The design parameters as given above are proved to be in safe region and it suitable in further development. With these results the robot is developed for inspection purpose in the nuclear power generation and waste management. Forward kinematics using Denavit –Harternberg approach is done to find the accurate end position of the robot by both analytical and geometrical approach.

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