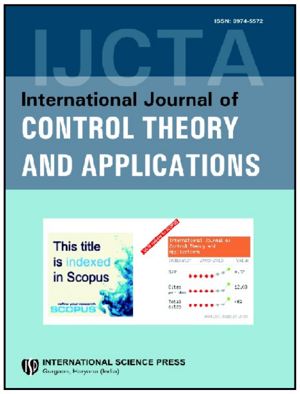

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Analytical and software method of Workspace Analysis for a Seven Degrees of Freedom Inspection Robot

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Abstract: Now-a-days robots need to be engaged a space for themselves in our everyday routine life. Present robots are capable to execute the complex tasks like Space Investigation, Nuclear Inspection, Manufacturing sector, and etc. to the simple jobs like pick and place operations in industries. The robots are recognized to execute their specified task in the three dimensional space. The end-effector which is the major part of the robot is planned in such a way that it follows the predicted trajectory within its working environment efficiently. For the accurate functioning of the robot the control above each and every links and joints is to be ensured in the robot systems. The position and orientation of the end-effector would be precisely controlled to obtain the smooth function and positioning of the robot. A newly designed articulated robot is expected to carry out the inspection tasks. That robot configuration must effectively serve as a substitute aimed at a human skilled worker, who would otherwise expose to dangerous and hazardous environments. The main objective of this paper is to propose a suitable mechanical configuration of the robot arm for inspection task and also to calculate the kinematics and workspace limits of the robot arm using analytical and software simulation method. The stable mathematical model is to be required to indicate the end effector motion and joint-link motions. This type of mathematical model is known as Kinematic Model. Modelling and simulation is an important aspect in robotic field. Significant of the workspace is very important to the operation of manipulators arm. The system can perform a given motion if the whole trajectory lies continuously within the workspace of the manipulator. This paper deals with the workspace analysis for a specially designed Seven Degree of Freedom robot for nuclear inspection purposes. The CAD model of robotic arm is made using CATIA V5 software and its simulation performed on Workspace Simulation Software. From this work the effective workspace drawing of the designed robot manipulator was obtained successfully.

Keywords**:** Robot modeling, Inspection Robot, Workspace Analysis, Seven Degree of Freedom,

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 softwares. These softwares reduced the risks in development process. Modern software like CATIA, ADAMS is now made available to generate workspace in 3-D space. Particularly in the departments like inspections in nuclear industries, the safety and the precision shaped the demand for new robots. In nuclear power stations many stainless steel canisters are used to store vitrified intermediate level wastes. These storage tanks are prone to defects frequently at the weldments. These welds need to be inspected and examined throughout their service life for signs of damage and defects.

In this work a newly designed articulated robot is expected to carry out the inspection tasks. That robot system must effectively serve as a substitute for a human worker, who would otherwise exposed to a dangerous and hazardous environments like nuclear industries.

Today, the industrial area has become an important application field of robotics. Special purpose automated machines, designed to perform precise functions and programs in a working process, carry out most of industrial manufacturing. Numerous technological operations can be substitute in working process through implication of the manipulator arms. The manipulator – robot arm presented in this paper can serve a robotic assistant to humans which are developed for inspection purposes in nuclear industries. Similarly G. Mansour et al. have developed a dynamic model of the human upper fringes a spatial mechanism with seven degree of freedom [1]. This model is developed to inspect the movement of the orthopaedic problem patient. The desired input motions are given and simulated to determine the torque and forces acting under different loads.

R. Mellah and R. Toumi used neural-fuzzy system to investigate trajectory control of already existing PUMA560 robot [2]. The designed system provides to be a universal approximate technology. The control-oriented fuzzy neurons and decision-oriented fuzzy neurons are used to identify the inverse dynamic model and to find a suitable input that drives the manipulator to follow the desired trajectory respectively. X.G. Fu et al. have introduced his new auto-inspection technology type robot system for weld inspection in nuclear pipes. Robot system consists of half clamp configuration as end effector 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. 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. An Analytical method is used to find the Workspace of the manipulator by Khushdeep Goyal and Davinder Sethi. They analyzed the workspace of RV-M1 MITSIBUSHI ROBOT and 3DOF spatial manipulator, which are modeled using the Denavit-Hartenberg representation [3]. The work space is found by obtaining the singularities of the robot as shown in Fig.8. The wrist computes the workspace of the robot by means of these singularities. Then the MATLAB code is developed which generates the workspace of the robot. Gigi Naidin et al, have made a workspace drawing from a 6DOF arm manipulator with RRRRR configuration [4].

The authors made performance analysis of this industrial manufacturing robot. They have used many types of software to do this research work, like Autodesk for preliminary design, mathematical model is made using Sim Mechanics for the mechanical structure and Sim Hydraulics for hydraulic drive, Simulink to complete modeling, MATLAB2007 to analysis of results and Workspace to spatial evolution. Work Space 5 software is utilized to realize the SAT model and maximum workspace.Using the Jacobian rank deficiency condition Malek et al, established a method to find the boundary of the geometric entity [5]. One of the entities is swept along the other entity to define the constraint functions, which gives the workspace of robots.An optimization approach is given by Snyman *et al.*, to determine the workspace of robotic manipulator [6].

In their method first the radiating point is found for the manipulator. From the rays radiating from that point the suitable points are determined. By investigating the intersection of the rays the workspace of the robot is developed. This method is to be applied with necessary accessories. A. Cherfia and A. Zaatri determined the geometrical model of a constrained three degree of freedom parallel robot [7]. The workspace analysis is done by geometric method and numerical calculation. To ensure zero singularity the jacobian matrix is also determined. T. Chettibi and P. Lemoine have given a simple method to generate the trajectory for serial manipulators [8].

The non-linear optimization program is developed using an approximation of joint position and orientation variables by means of mathematical algebraic polynomial splines, which interpolate a set of control points. Then, the optimization problem is solved using a sequential quadratic programming method for the unidentified transmission time and the unknown position of control points, while minimizing a cost function and respecting elecro-mechanical constraints. The determination of Workspace of the complex robotic manipulator is done by Ricard and Gosselin. The authors presented a new method of workspace generation by using joint limits [9]. These joint limits are implemented in obtaining the equations to generate limiting curves, which are separated at the common intervals and these curves are validated. These curves form the environment of workspace of the robot. The algebraic method is involved in determination of the workspace for a 3DOF Robotic arm by Ceccarelli [10]. The author also developed an algorithm to synthesize these types of robots. The non-linear equations are developed from the synthesis results. The unknown variables of these equations are calculated which gives the structure of the workspace. This method can be applied to any robot to find its workspace.

A study of applying jacobian matrix in designing 6DOF robot arm is done by NoorfarahIzzaBintiMustaffa Kamal [11]. The jacobian matrix is applied on designing the six DOF robot arm. MATLAB software is used to demonstrate the working space of the robot arm. The author has presented the types of robots and their applications. Development of a Jacobean model for 4-axes indigenously developed SCARA system is done by T.C.Manjunath and C.Ardil [12]. The Jacobean model is developed for a 4-axes SCARA robot, which is used in studying the relation between the forces and velocities in the working condition of the robot. The authors have designed a SCARA robot with four Degrees of freedom. In this Trajectory planning is done in Tool Configuration Space. The relationship between the speed of tip of end effector and speed of the joints is calculated as jacobian matrix. The authors also developed the algorithm for manipulating the jacobian matrix. Graphically the velocities at the joints are plotted using MATLAB software. Soheil Zarkandi and Mohammad Reza Esmaili have prepared a kinematic redundancy method to avoid singularities of any manipulators [13]. The 5R manipulator which had singular loci within the workspace is modified by including the two prismatic joints with configuration RPRRRPR. This method proved to be a superior one in re-designing the robots.

2. ROBOT MODELLING

The mechanically stable configuration of the robot is modeled using three dimensioning modeling software CATIA as shown in Figure 1. The effective utilization of the screw jack mechanism has been implemented for the base up and down movement of the manipulator. Robotic configuration gives us the exact knowledge of work volume and space of operation of robot. As per the joint and link movements, the configurations are of different types. The arms of the robot have two universal joints for flexible movement of the arm which was utilized for maneuvering around the outer or external surface of the cylindrically shaped steel canister. The robot manipulator comprises of totally seven degrees of freedom. They are following,

- Robot Base twist (T)
- Base lift up & Down (P)
- Arm 1 – two rotational motions (2R)
- Arm 2 – two rotational motions (2R)
- End effector revolute motion (R)

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

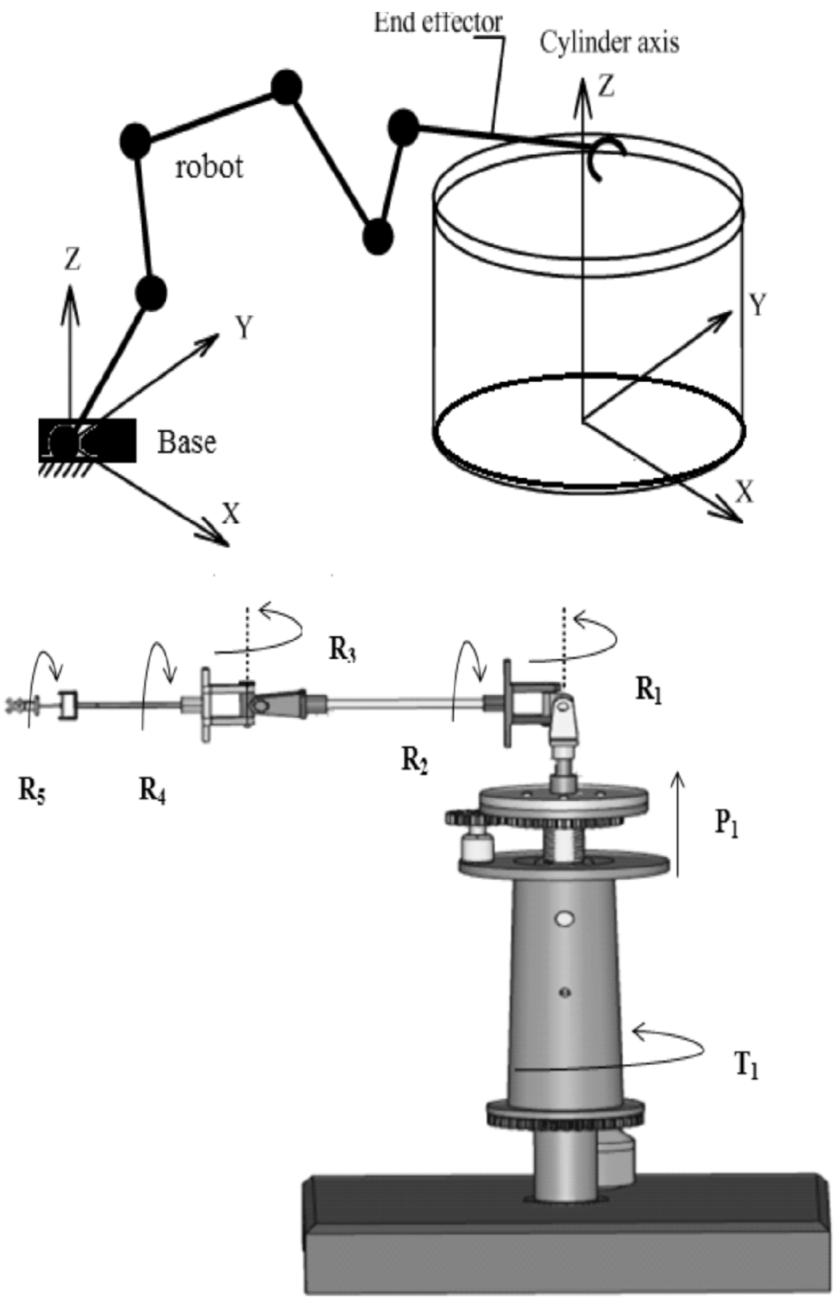

Figure 1: Robot modeled in CATIA illustrating the 7DOF

3. KINEMATIC MODELLING

The Kinematic model is one of the major studies of robot design which gives the relationship between the position and orientation of the end-effector and spatial position of the joint links. In other words it is defined as analytical study about the points of motion of a robot arm with respect to a fixed or defined reference coordinate system without regard to the forces. The manipulator of a serial robot is, typically, an open kinematics chain. A robot manipulator includes hyperlinks linked with the aid of joints. The links of the manipulator will also be regarded to kind of a kinematic chain. The industry finish of the kinematic chain of the manipulator is called the end effector and it is equivalent to the human hand. The tip effector generally is a gripper or may also be designed to perform any preferred project such as welding, assembly, and so on. The fig.1 shows the configuration of the serial manipulator as an example which is formed by means of a set of undependably moved joints. The kinematic modeling which requires basically both the forward and inverse kinematics solutions. The link parameters are commonly used in both the kinematics solutions. The kinematic equations was developed which denotes the inputs and outputs of kinematic solutions through geometrical of matrix approach.

4. JOINT RANGES

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.

Table 1
Joint Ranges

Sl no	*Joint angle*	*Joint Range (in degrees)*
1	θ_1	-360 to +360
2	$\theta_2 = 0$, d	0 to 240 mm
3	θ_3	-90 to +60
4	θ_4	-90 to +60
5	θ_5	-60 to +90
6	θ_6	-60 to +90
7	θ_7	-120 to +120

5. WORKSPACE ANALYSIS

The workspace or work-volume of a robot is calculated by an analytical method. The method is applicable to kinematic chains that can be easily modeled using the Denavit-Hartenberg representation for serial configured kinematic chains. This method is founded upon analytical criteria for defining singular behavior of the each designed mechanism. By manipulating the Jacobian matrix of the robot by the row rank deficiency condition, the singularities of the links are computed then these singularities are substituted into the constraint equations which were predetermined to parameterize singular surfaces. The boundary conditions of the robot joints are substituted to obtain the other set of singularities. These singularities are substituted in the wrist vector to obtain the range of motion of the robot wrist in three dimensional spaces, which is the workspace of the Robot.

Table 2
D-H Parameter Table

#	α_i *(degree)*	a_i *(mm)*	d_i *(mm)*	*Joint angle* 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

(A) Methodology

In order to analytically drive the expressions for boundary surfaces of robotic manipulators, it is necessary follow the following steps,

1. To develop a set of analytical criteria to obtain the orientation and positioning of the robot wrist in terms of generalized coordinates system.
2. Determine the boundary surfaces due to joint singularities associated with the set of variables, and
3. Determine the subgroup of the surfaces due to the robot joint limits. Combine all the surfaces to develop the workspace. The mathematics to determine above is explained in the following sections.

(B) Analytical Approach

To explore the specified work envelope of these seven degrees of freedom robot, the part co-ordinate diagram is developed for the designed robot as shown in the Figure.3, which demonstrates the complete information about the joints and links of the robot.

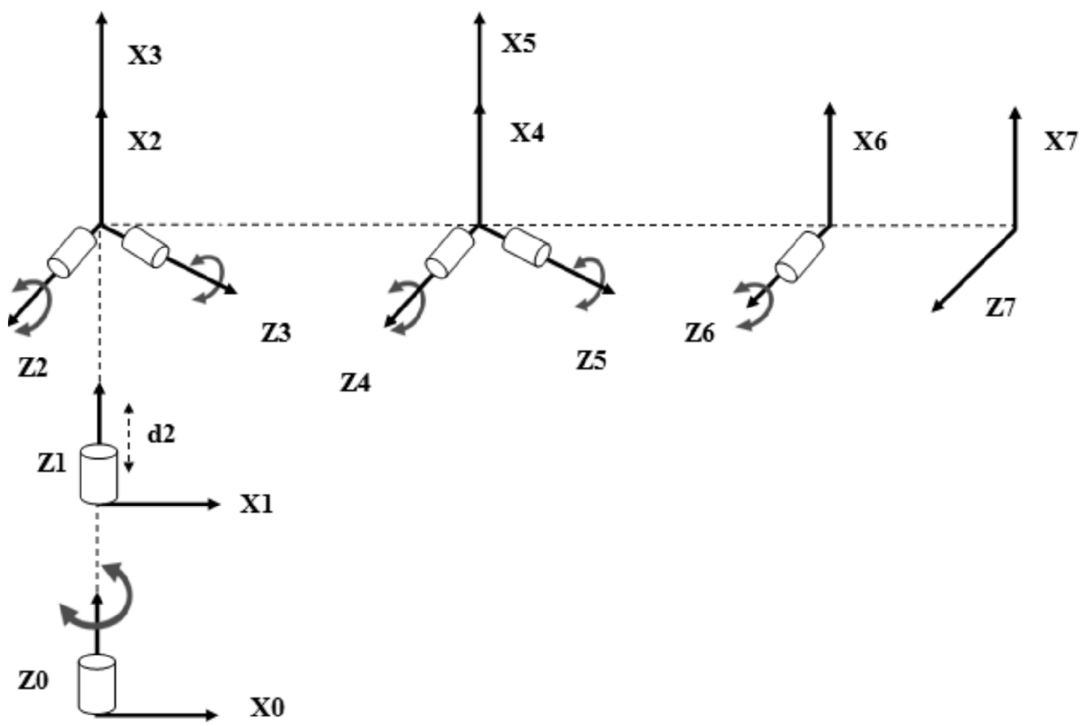

Figure 2: Part co-ordinate system of the robot

The illustration of the axis of the joints through the part coordinate system. To develop the part coordinate system the home or initial position of the robot is used. In the home position the value of X axis and Z axis of each joints are expressed as per the convention of Denavit-Hartenberg's kinematic matrix approach. The movement of the joints is also depicted in the diagram for easy understanding and clear illustration. For kinematic analysis the Part co-ordinate system as shown in Figure.4 is derived as per the convention of Denavit-Hartenberg's kinematic approach then consider the robot in maximum extended position to evaluate the reach of a seven degree of freedom.

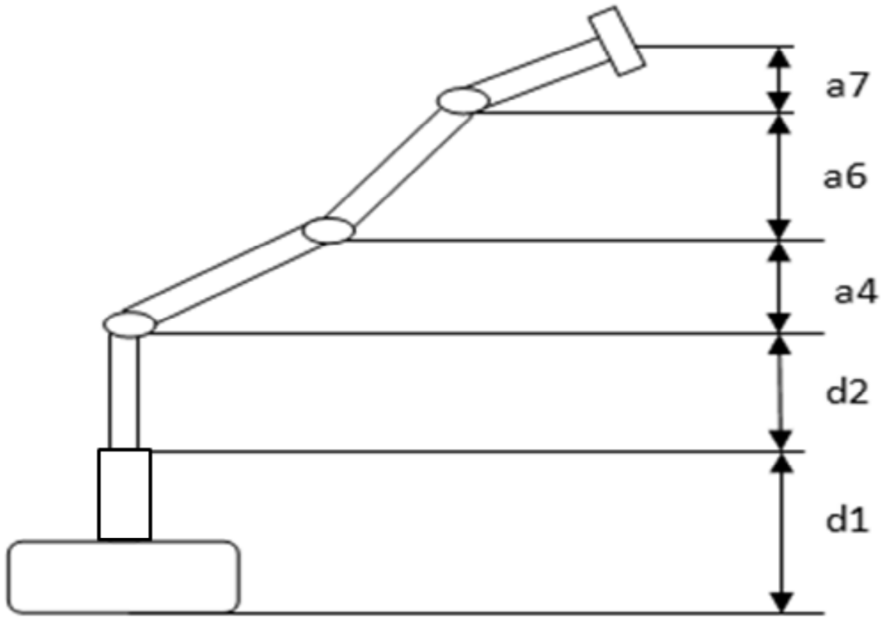

Figure 3: Schematic Structure of Robot showing the parameters

Considering the above Figure the tool-configuration vector w(q) is formulated. In this the variable q = θ.

$$w(q) = \begin{bmatrix} (c1c3c45 + s1s45)(c67\ a7 + c6a6) - c1s3(s67a7 + s6a6) + (c1c3c4 + s1s4)a4 \\ (s1c3c45 - c1s45)(c67\ a7 + c6a6) - s1s3(s67a7 + s6a6) + (s1c3c4 - c1s4)a4 \\ s3c45(c67a\ 7 + c6a6) + s3c4a4 + c3s67a7 + c3s6a6 + d2 + d1 \\ \hline -[\exp(q7/\pi)]c1c3s45 + s1c45 \\ -[\exp(q7/\pi)]s1c3s45 - c1c45 \\ -[\exp(q7/\pi)]s3s45 \end{bmatrix} \quad (1)$$

This tool configuration vector is used to specify the maximum limits of the robot.

$$\begin{bmatrix} -2\pi \\ 0 \\ -\pi/2 \\ -\pi/2 \\ -\pi/3 \\ -\pi/3 \\ -2\pi/3 \end{bmatrix} \le \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} q \le \begin{bmatrix} +2\pi \\ 240\ mm \\ +\pi/3 \\ +\pi/3 \\ +\pi/2 \\ +\pi/2 \\ +2\pi/3 \end{bmatrix} \quad (2)$$

The above equation specifies that that the base joint is free to move all round 360 degrees. The limits of other joints area also clearly specified.

6. SOFTWARE INFERENCES

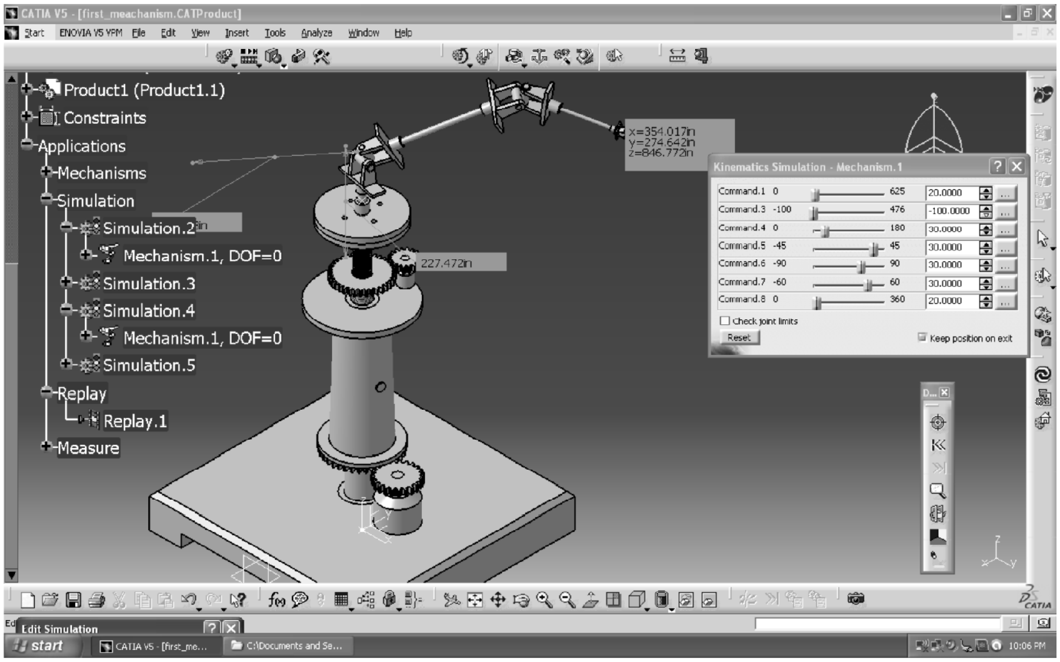

Figure 4: Robot model in CATIA software demonstrating the link movements

The above figure 5 stipulates the simulation done in the CATIA modeling and mechanism designing software. The second figure specifies the command specification to alter the robot motions. The CAD model of robotic arm is made using CATIA V5 software and its simulation performed on Workspace Simulation Software.

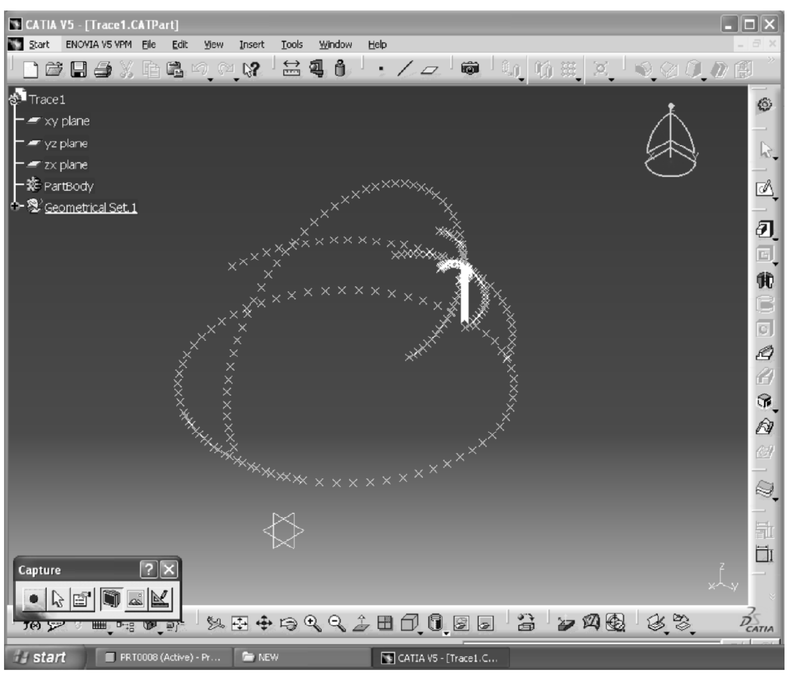

Figure 5: The work envelope of the robot in CATIA software

The robot is allowed to move in all possible motions. The software is assigned as to trace the workspace. The tip of the end-effector makes a mark as it traverse the space in the environment. From the Figure 6 it is clear that robot can navigate the maximum workspace. The 3D Workspace has been achieved by changing the joints limits between the minimum and maximum values. Therefore individual workspaces of each link are discovered sequentially and then attach each possible 2D target points to the next target points. The software is made to generate the planar workspace in the environment. Figure clearly indicates the maximum reach of the robot in the 3-D space.

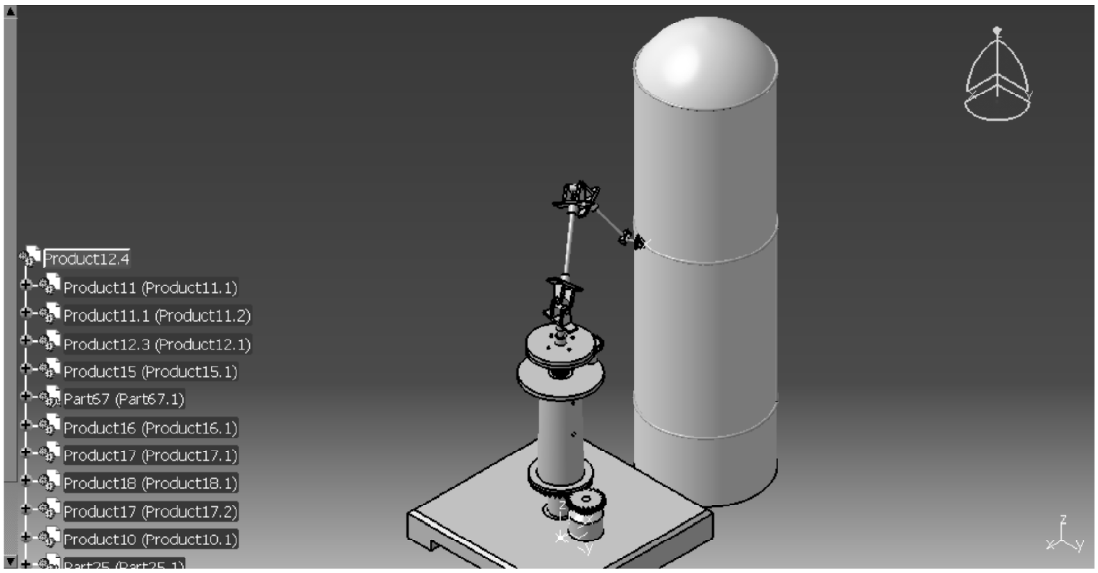

Figure 6: Simulation window of the Robot for cylinder outer inspection

The simulation is done in the CATIA software to demonstrate the actual practical application in the real time environment created by the software. This type of simulation before the real practical application is very useful to fabricate the robot and make changes as per the rectifications.

6. CONCLUSION

The importance of workspace analysis is understood. This paper gives the past researchers in workspace analysis and a attempt to do workspace analysis for the specifically designed new inspection robot. The software results proved that the robot is feasible one to work in such an unstructured environment with such a wider workspace. The pre-requisites of workspace generations are also demonstrated in detail such as the link frame arrangement and D-H table. The designed CAD model can be simulated on workspace simulation software. This software can give you the exact simulated view of operational space. The robot mechanical configuration design is made and simulated in CATIA software. The images of the CATIA working tabs are added importance in this paper. Since the structures of the nuclear waste storages are cylindrical in structure the simulation is presented to validate the working space of the robot. This simulation proves that the robot is totally capable of perform the given task.

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