# Forward Kinematic Analysis, Simulation & Workspace Tracing of Anthropomorphic Robot Manipulator By Using MSC. ADAMS

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**ABSTRACT**: The Robot kinematics deals with the position of links which are connected with the help of joints, which gives the position and orientation of every link present in the robot manipulator to place the end-effector to the required target. A kinematic model of the anthropomorphic robot manipulator was developed using multibody dynamic software called MSC. Automated Dynamic Analysis of Mechanical Systems (ADAMS) which represents the human arm. The shoulder joint is considered as spherical joint and elbow joint as a revolute joint. Kinematic equations and Software model is developed to compare and verify the working of the robot manipulator. The Workspace of the robot manipulator was traced to show the maximum and minimum working area of the manipulator. The workspace of the robot manipulator is traced in MSC. ADAMS to show the working region of the manipulator.

**KEYWORDS**: Anthropomorphic, End-effector, Forward Kinematics, MSC. ADAMS, Workspace.

## I. INTRODUCTION

A manipulator can be schematically represented from a mechanical viewpoint as kinematic chain of rigid bodies (links) connected by means of revolute or prismatic joints. One end of the chain is fixed to a base, while an end-effector is attached on the other end [1].

Robot arm kinematics deals with the analytical study of the geometry of motion of a robot arm with respect to a fixed reference coordinate system as a function of time without regard to the forces / moments that cause the motion [2]. Kinematic equation gives the relationship between the joint displacement and the position and orientation of end-effector is determined. Determining the final position & orientation of the end effector depending upon the joint angles is known as forward kinematics and finding the joint angles depending upon the position of end effector is known as inverse kinematics [3].

An end effector is a device that attaches to the wrist of the robot arm and enables the general – purpose robot to perform a specific task. It is sometimes referred to as robot's "hand" [4].

In robotics, end effectors are fixed /attached to the robot arm, which interacts with the surroundings like a human hand having fingers to lift or grab. Gripper is an end effector or tool to grab any object or any tools, which can be used for welding, painting etc. The gripper performs tasks such as picking, grasping or holding by various means for different applications [5].

Workspace refers to the space within which the robot can manipulate its wrist end. Workspace is also referred as working volume of a robot manipulator, which becomes an important indicator to measure the performance of the robot manipulator. The shape and size of the workspace / work volume depends upon the kinematic configurations of the robot manipulator [6].

The MSC. ADAMS software is capable of simulating kinematics and kinetics behaviour of any mechanical system. The dynamic behaviour of a system can be compared with the real models that can be simulated with an acceptable variation in the result [7]. MSC. ADAMS software tool plays very important tool for rapid virtual prototyping which reduces the design failure or feasibility of the design. Real prototype model takes lots of time to test because it needs testing setup and environment. MSC. ADAMS incorporates all the required dynamics virtually which is required for real testing conditions. Various modeling files can be imported in MSC. ADAMS from SolidWorks, Creo, Catia or Solidedge etc. [8].

## II. RELATED WORK

The robot manipulators are classified depending upon their configuration, such as Cartesian robot, Cylindrical robot, Spherical robot, SCARA robot, Articulated robot, Parallel robot. These robots consist of revolute joint or prismatic joints to meet the desired motion. The revolute and prismatic joints are very simple and are not complicated to use. These joints have one degree of freedom, so that linear motion is achieved in case of prismatic joint and rotary motion is achieved in case of revolute joints. Kinematic analysis, Simulations is performed by using MATLAB simulink or sometimes VRML (Virtual Reality Modeling Language) is used to carry out analysis part. This paper deals with a new robot manipulator, which uses a spherical joint. Spherical joints are very complex in nature due to its number of degrees of freedom. Sometimes it becomes necessary to deactivate at least one degree of freedom to avoid redundancy error. This robot manipulator closely resembles the functions of a human arm. The kinematic equations are developed and verified in MSC. ADAMS by comparing the analytical results and software results.

## III. METHODOLOGY

The block diagram represents the step by step methodology for the kinematic analysis, simulation and workspace tracing robot manipulator is shown in Figure 1.
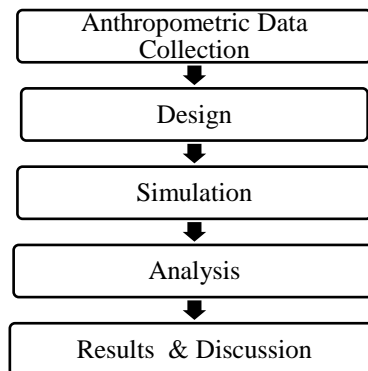


Fig.1 Flow chart of Methodology

### III.1 ANTHROPOMORPHIC DATA COLLECTION

Anthropometry in physical anthropology refers to the measurement of the human individual for the purposes of understanding human physical variation. The anatomy of human arm is shown in Figure 2.
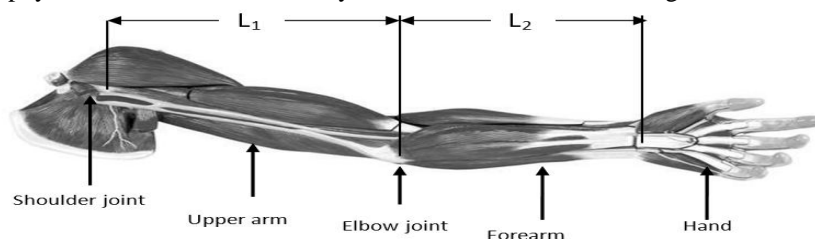


Fig.2 Anatomy of Human Arm

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Anthropometric dimensions selected for upper arm and forearm for the robot manipulator are [9]: $L_1$ = 310 mm or 0.31m and $L_2$ = 280 mm or 0.28 m.

### III.2 ANATOMY OF ANTHROPOMORPHIC MANIPULATOR

The model of 3 DOF robot manipulator is shown in Figure 3. The diagram of robot manipulator is similar to human arm. The robot has total two joints i.e. one spherical joint and one revolute joint. The revolute joint connects between upper arm and forearm, the spherical joint connects upper arm and actuator (guideway, motor etc). The spherical joint plays very important role in this model. The end-effector is located at the end of forearm which is similar to wrist end.
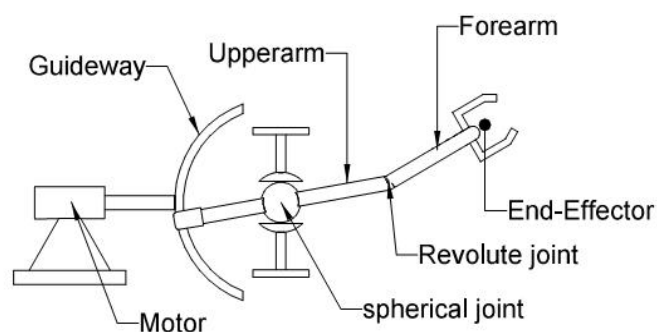


Fig.3 Anatomy of Robot Manipulator

### III.3 WORKING PRINCIPLE OF ANTHROPOMORPHIC MANIPULATOR

The 3-DOF robot manipulator has one spherical joint and one revolute joint. The spherical joint is supported by the cups which are fixed or grounded. Behind the spherical joint a link is extended as a slider which slides along the guideway. The guideway is connected to the motor shaft which is located behind the guideway as shown in the above figure. The joint connecting the forearm and upper arm is called revolute joint which is also called as elbow joint in human anatomy. The joint can rotate the forearm in upward or in a downward direction. When the motor rotates in clockwise/counter clockwise direction, the guideway which is connected to the motor also rotates so that the upper arm and forearm also rotates in clockwise/counter clockwise direction. When the slider moves along the guideway which is in the shape of an arc, the upper arm and forearm also moves in up and down directions. The 3-DOF robot manipulator is shown in Figure 4. $\theta_1$, $\theta_2$, $\theta_3$ are motor rotation angle, Upper arm rotation angle and Forearm rotation angle.
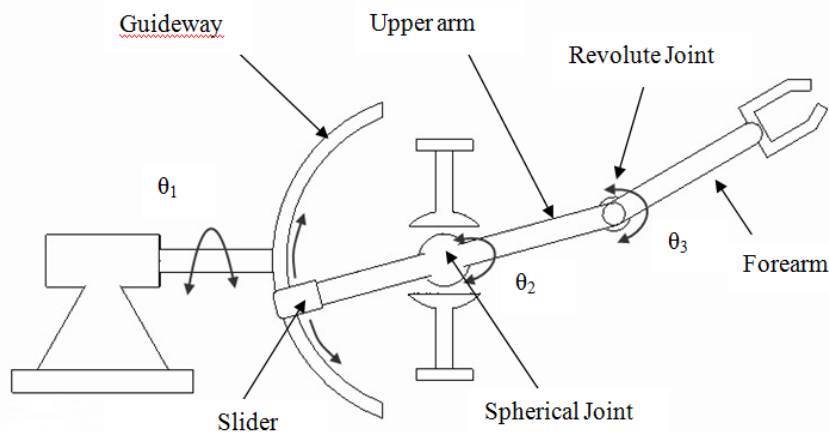


Fig.4 Working Principle of Robot Manipulator

## III.4 MODEL OF ANTHROPOMORPHIC ROBOT MANIPULATOR

A virtual model of robot manipulator built in MSC. ADAMS software package interface of MSC. ADAMS is shown in Figure 5.
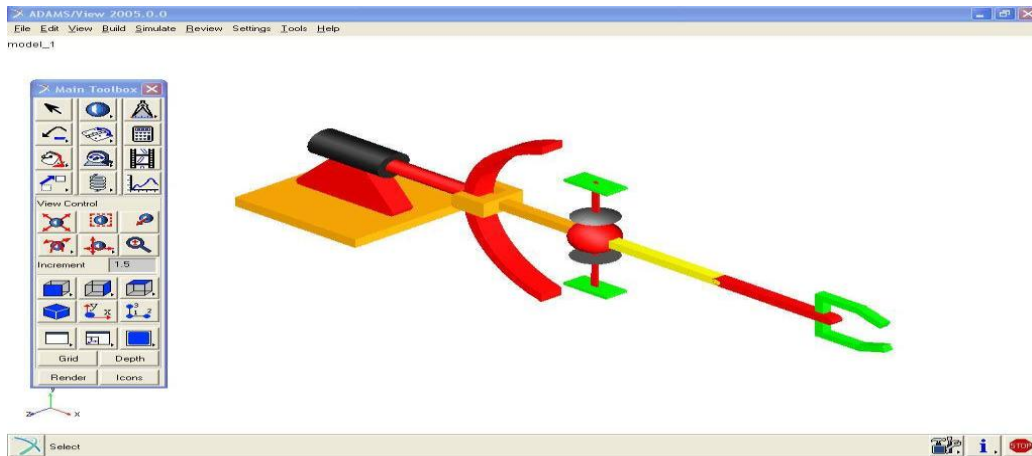


Fig.5 Model of Robot Manipulator in MSC. ADAMS

## III.5 FORWARD KINEMATIC EQUATIONS

The Forward kinematic equations are developed based on Denavit – Hartenberg parameters [10].

The coordinate frames are identified base on the three criteria:

a)       The $z_{i-1}$ axis lies along the axis of motion of the $i^{th}$ joint.

b)       The $x_i$ axis is normal to the $z_{i-1}$ axis, and pointing away from it.

c)       The $y_i$ axis completes the right – handed coordinate system as required.

From above rules, the location of coordinate frame '0' is assigned for the supporting base, as long as the $z_0$ axis lies along the axis of motion of the first joint.

The last coordinate frame ($n^{th}$ frame) can be placed anywhere in the hand, as long as the $x_n$ axis is normal to the $z_{n-1}$ axis

The D-H representation of a rigid link depends on four geometric parameters associated with each link.

The four parameters are defined as follows [11]:

1)       $\theta_i$ is the joint angle from the $x_{i-1}$ axis about the $z_{i-1}$ axis.

2)       $d_i$ is the joint distance along the $z_{i-1}$axis.

3)       $a_i$ is the offset distance from the intersection of the $z_{i-1}$ axis with the $x_i$ axis to the origin of the $i^{th}$ frame along the $x_i$ axis (or the shortest distance between the $z_{i-1}$ and $z_i$ axes).

4)       $\alpha_i$ is the offset angle from the $z_{i-1}$ axis to the $z_i$ axis about the $x_i$ axis.

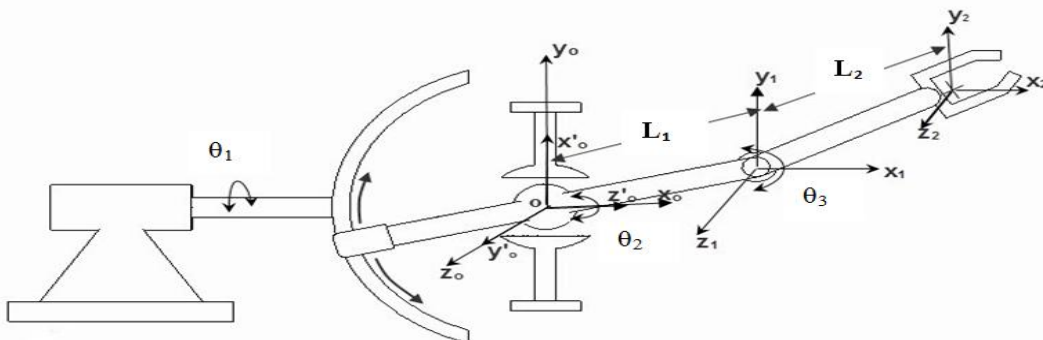The frame assignment according to the D-H parameters for the 3-DOF robot manipulator is shown in Figure 6.



Fig.6 Frame Assignment for Robot Manipulator

The Joint-Link parameters are identified and these are tabulated in Table 1.

Table -1 Joint-Link Parameters for 3-DOF Robot Manipulator

| Joint i | $\theta_i$ | $\alpha_i$ | $a_i$ |
|---|---|---|---|
| 1 | $\theta_1$ | -90° | 0 |
| 2 | $\theta_2$ | 0 | $L_1$ |
| 3 | $\theta_3$ | 0 | $L_2$ |

$$T = T(z, \theta_1) * T(z, \alpha_1) * T(z, \theta_2) * T(z, \theta_3) \tag{1}$$

$$T = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_\alpha & -S_\alpha & 0 \\ 0 & S_\alpha & C_S & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T = \begin{bmatrix} C_1 & 0 & -S_1 & 0 \\ S_1 & 0 & C_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_2 & C_2 & 0 & L_2S_2 \\ -C_2 & S_2 & 0 & -L_1C_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_3 & -S_3 & 0 & L_2C_3 \\ S_3 & C_3 & 0 & L_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$T = \begin{bmatrix} C_1 & 0 & -S_1 & 0 \\ S_1 & 0 & C_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_2C_3 + C_2S_3 & -S_2S_3 + C_2C_3 & 0 & S_2L_2C_3 + C_2L_2S_3 + L_1S_2 \\ -C_2C_3 + S_2S_3 & C_2S_3 + S_2C_3 & 0 & -C_2L_2C_3 + S_2L_2S_3 - L_1C_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T = \begin{bmatrix} C_1S_2C_3 + C_1C_2S_3 & -C_1S_2S_3 + C_1C_2C_3 & -S_1 & C_1S_2L_2C_3 + C_1C_2L_2S_3 + C_1L_1S_2 \\ S_1S_2S_3 + S_1C_2S_3 & -S_1S_2S_3 + S_1C_2S_3 & C_1 & S_1S_2L_2C_3 + S_1C_2L_2S_3 + L_1S_1S_2 \\ C_2C_3 - S_2S_3 & -C_2S_3 - C_2C_3 & 0 & C_2L_2C_3 - S_2L_2S_3 + L_1C_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$x = C_1S_2L_2C_3 + C_1C_2L_2S_3 + C_1L_1S_2 \tag{5}$$
$$y = S_1S_2L_2C_3 + S_1C_2L_2S_3 + L_1S_1S_2 \tag{6}$$
$$z = C_2L_2C_3 - S_2L_2S_3 + L_1C_2 \tag{7}$$
$$x = (S_2L_2C_3 + C_2L_2S_3 + L_1S_2)C_1 \tag{8}$$
$$y = (S_2L_2C_3 + C_2L_2S_3 + L_1S_2)S_1 \tag{9}$$
$$z = L_1C_2 + L_2\cos(\theta_2 + \theta_3) \tag{10}$$

$\therefore$ The position of end-effector is obtained from the following equations

$$P_x = \{L_1\sin\theta_2 + L_2\sin(\theta_2 + \theta_3)\}\cos\theta_1 \tag{11}$$
$$P_y = \{L_1\sin\theta_2 + L_2\sin(\theta_2 + \theta_3)\}\sin\theta_1 \tag{12}$$
$$P_z = L_1\cos\theta_2 + L_2\cos(\theta_2 + \theta_3) \tag{13}$$

## IV. RESULTS & DISCUSSIONS

### IV.1 COMPARISON BETWEEN ANALYTICAL & MSC. ADAMS RESULTS

$\theta_1$ (Motor rotation) is kept zero i.e. no motion, whereas $\theta_2$ (Upper arm angle) & $\theta_3$ (Forearm angle) are varied up to 70° and 140°. The position of end-effector for various joint variables is determined analytically & from MSC. ADAMS software tool are shown in Table 2 and 3. $\theta_1$= zero (constant), $\theta_2$ = varies 10° (up to 70°), $\theta_3$ = varies 20° (up to 140°) Px, Py, Pz are in 'mm' & $\theta_1$, $\theta_2$, $\theta_3$ are in degrees. Manipulator moving up (while moving up joint angles are taken as positive)

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Table-2: Iteration of Robot Manipulator For $\theta_1=0˚$, $\theta_2=10˚$ to $70˚$ & $\theta_3=20˚$ to $140˚$

| Joint angles | | | Analytical Results | | | MSC. ADAMS Results | | | Error |
|---|---|---|---|---|---|---|---|---|---|
| $\theta_1$ | $\theta_2$ | $\theta_3$ | $P_x$ | $P_y$ | $P_z$ | $P_x$ | $P_y$ | $P_z$ | |
| 0 | 10 | 20 | 193.830 | 0 | 547.777 | 193.830 | 0 | 547.777 | 0 |
| 0 | 20 | 40 | 348.513 | 0 | 431.304 | 348.513 | 0 | 431.304 | 0 |
| 0 | 30 | 60 | 435.0 | 0 | 268.467 | 435.0 | 0 | 268.467 | 0 |
| 0 | 40 | 80 | 441.75 | 0 | 97.473 | 441.75 | 0 | 97.473 | 0 |
| 0 | 50 | 100 | 377.473 | 0 | -43.222 | 377.473 | 0 | -43.223 | 0.001 |
| 0 | 60 | 120 | 268.467 | 0 | -125.0 | 268.467 | 0 | -125.0 | 0 |
| 0 | 70 | 140 | 151.304 | 0 | -136.460 | 151.304 | 0 | -136.460 | 0 |

Graphical comparison between analytical & MSC. ADAMS results are shown in Figure 7 and Figure 8. The values of position of end-effector, Px in 'mm' and Pz in 'mm' from Table 2 are plotted graphically. The values obtained from analytical method and MSC. ADAMS results are same due to which the two curves overlap. The x-axis is simulation time and y-axis is position. Blue colour curve indicate analytical results and red colour curve indicate MSC. ADAMS results.
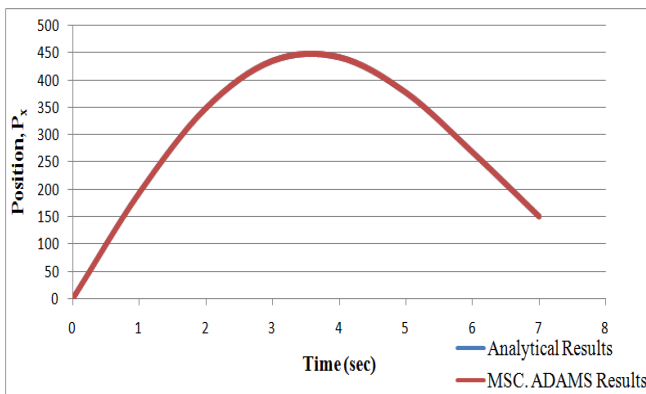


Fig. 7 Graphical Plot of Position Px against Time
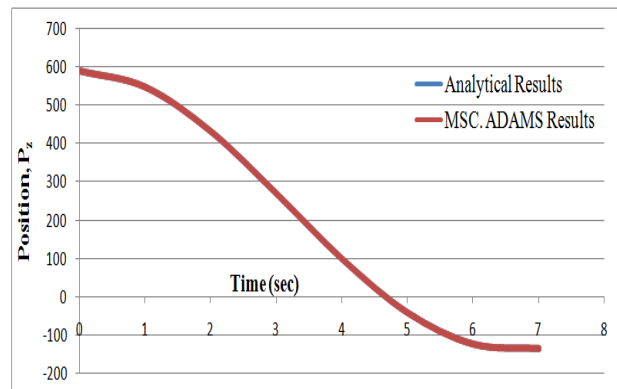


Fig. 8 Graphical Plot of Position Pz against Time

### IV.2 WORKSPACE TRACING

The workspace of a manipulator is the volume in which, the end-effector of the manipulator reaches the points comfortably. The workspace is affected by the geometry of the manipulator as well as the joint angles / configuration. For example, a revolute joint may be limited to less than a full 360° of motion. Some joints may not be able go beyond $90^o$ due to kinematic chain or the constrained. The Figure 11 shows the side view of workspace of robot manipulator.
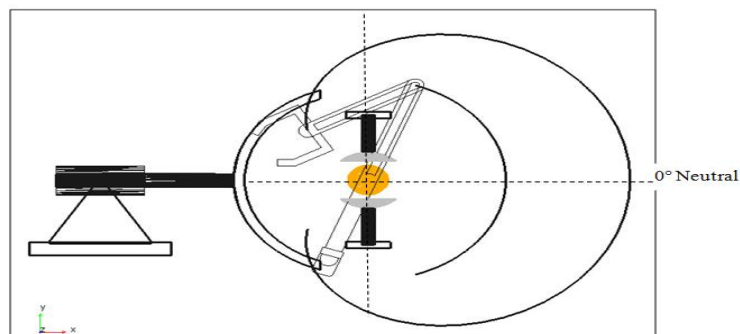


Fig. 11 Side View of Workspace of Robot Manipulator

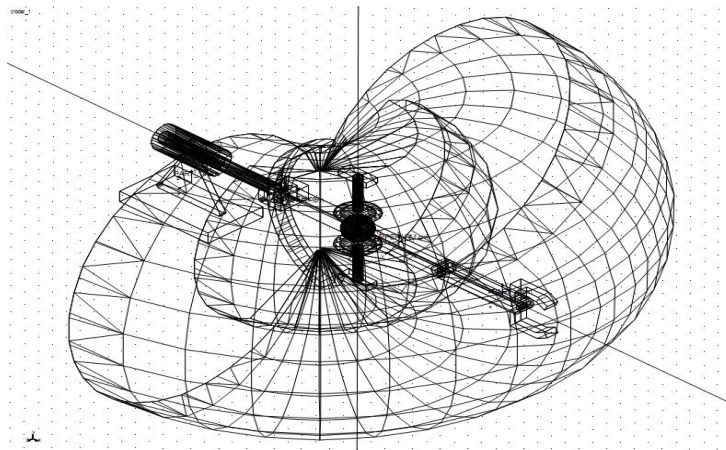Figure 12 represents the wireframe view of workspace of the manipulator.



Fig. 12 Wireframe view of workspace of robot manipulator

## V. CONCLUSION

A complete virtual model of 3 Degrees of Freedom robot manipulator is developed by using anthropometric data. Simulation of the model was performed by using MSC. ADAMS. All desired motions were achieved by using a spherical joint in robot configuration. The results obtained from analytical and MSC. ADAMS are same and validates the developed equations. Workspace profile of the robot manipulator was traced to show the profile of working region of manipulator. The performance and feasibility of the design of robot manipulator can be checked using MSC. ADAMS before going for physical model which is time consuming process.

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