Design and Simulation of a Robotic Arm for a Service Robot

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***Abstract*—This paper focuses on designing and simulation of an interactive robotic arm for pick and place and service applications. The robot is expected to have image processing and voice recognition capability. The mechanical structure is simulated using forward kinematics and for this, Denavit-Hartenberg parameter method is used for the proposed design and hence the mechanical structure is simulated in MATLAB and SolidWorks. SolidWorks structure comprises the proposed link lengths and joints which were used for forward kinematics calculations and workspace simulations. Static and dynamic torques are taken into consideration to determine the torques of joint motors. It is expected to find the design requirements and assess the scope of the robot arm before its manipulation.**

Keywords—Degrees of Freedom, Forward Kinematics, DH parameters, Robotics ToolBox

I. INTRODUCTION

According to the International Federation of Robotics, a service robot is "a robot that performs useful tasks for humans or equipment excluding industrial automation application [1]". These are typically complex systems requiring the collaboration of knowledge from various disciplines. Applications of these platforms are widespread to military, healthcare, education, entertainment, domestic, space, mining and much more. Autonomous mobile robots are made basically intelligent. They are capable of sensing the environment and adjust accordingly and carry out the specified task accordingly. The most important aspect of this type of robots is their mobility [2-4].

Service robots thus have to be able to actively interact with potential users in their surroundings and to appropriately offer their services for specially elderly and disabled. To this extent, various service robots have been introduced such as vacuum cleaning robots, home security robots, entertainment robots, and guide robots. Especially robots that are able to assist the elderly are becoming popular with the dramatic increase in the aging population and among disabled populations such as renowned soldiers. This reduces the cost of care for these sets of citizens. Therefore robotic aid systems have become popular and rapidly advancing field of technology [5-9].

During the process of developing a service robot, the reach of the arm, maximum length with the links and angular limitations are important parameters to be considered. The modeling, analysis and implementation of manipulators involve the study of their kinematic behavior. The creation of a kinematic model is critical to simulate the sequence of activities of the robot and check each aspect of the relative movements related to the joints and work space. Forward kinematics refers to the use of the kinematic equations of a robot to compute the position of the end-effector from specified values for the joint parameters. But what is important in a robot manipulator is the inverse kinematics which is finding the corresponding values of the joint angles in order for the end effector to move to a certain position with a certain orientation.

Following sections of this paper will discuss in detail scope of the robot arm, kinematic analysis, simulations of the robot arm, trajectory planning, physical model and finally the conclusions.

II. SCOPE OF THE ROBOT ARM

The scope of the robot is determined so that it is capable of performing pick and place tasks up to a reach of 65 cm. This range is selected so that the arm can successfully replace a human hand. As the robot arm is intended to use for service purposes it should have the length of at least the human hand. A payload of 350g is selected and hence motor torque is determined based on this value of payload. There are 6 Degrees of Freedom so that the robot manipulator will cover a larger envelope in space. Integration of electrical and mechanical systems is shown in Fig. 1.

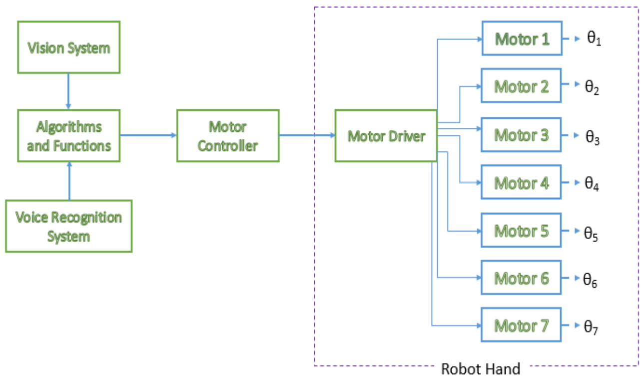

Fig. 1. System Overview

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TABLE I: COMPONENT SPECIFICATIONS

Motor Joint	Maximum Torque (kg cm)	Weight of Selected motors (g)
1	36 (4.8- 7.4 V)	78.2
3	24 (4.8- 7.4 V)	68
4	10.6 (4.8- 6 V)	52
5	8.8 (4.8- 7.4 V)	60
6	8 (4.8- 6 V)	53

According to calculations of static and dynamic torque, the values obtained for each servo motor are mentioned in Table I.

Servo motor in the position 2 and 4, and motors in 6, 7, 8 positions will share the same torques as they are associated only with rotational movement. Here, position 1 refers to the base motor joint.

III. KINEMATIC ANALYSIS

Sequence of mechanical links connected together by actuated joints makes the serial link manipulator. That structure forms the kinematics chain and hence can be analyzed by Denavite- Hartenberg (D-H) parameter method. The results of this analysis are the matrices and finally the overall matrix T which expresses manipulator end-effector Cartesian position in terms of the joint coordinates. Calculated DH parameters are mentioned as in Table II by means of the DH matrix. Fig. 2 illustrates the frame assignment and frames are assigned at each joint to calculate DH parameters.

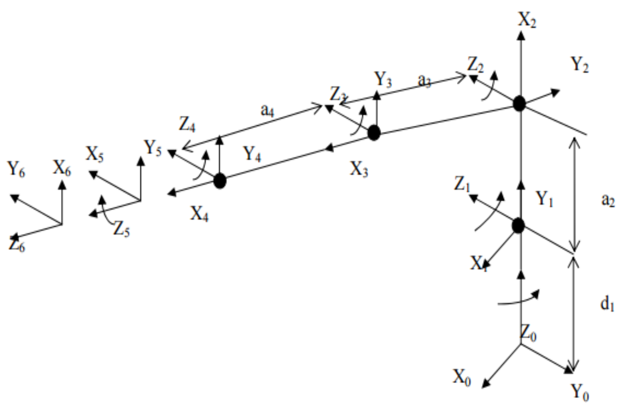

Fig. 2. Frame Assignment at each joint

TABLE II. THE DH MATRIX

Joint (i)	α_{i-1}	d_i	θ_i	a_{i-1}
1	90°	d_1	θ_1	0
2	0°	0	θ_2	a_2
3	0°	0	θ_3	a_3
4	90°	0	θ_4	a_4
5	90°	0	θ_5	0
6	0°	d_6	θ_6	0

In the case of the robot manipulator $a_2 = a_3 = a_4 = 6$cm, $d_1 = 6$cm and $d_6 = 4$cm. Hence the link transformation matrices for the 6 main joints are found as below.

$$ {}^0_1T = \begin{bmatrix} C\theta1 & -S\theta1 & 0 & 0 \\ 0 & 0 & -1 & -d1 \\ S\theta1 & C\theta1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^1_2T = \begin{bmatrix} C\theta2 & -S\theta2 & 0 & a2 \\ S\theta2 & C\theta2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^2_3T = \begin{bmatrix} C\theta3 & -S\theta3 & 0 & a3 \\ S\theta3 & C\theta3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^3_4T = \begin{bmatrix} C\theta4 & -S\theta4 & 0 & a4 \\ 0 & 0 & -1 & 0 \\ S\theta4 & C\theta4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^4_5T = \begin{bmatrix} C\theta5 & -S\theta5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ S\theta4 & C\theta4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^5_6T = \begin{bmatrix} C\theta5 & -S\theta5 & 0 & 0 \\ S\theta5 & C\theta5 & -1 & 0 \\ 0 & 0 & 1 & d6 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Overall DH matrix can be obtained from the above matrices as follows.

$$ T = {}^0_1T\ {}^1_2T\ {}^2_3T\ {}^3_4T\ {}^4_5T\ {}^5_6T \qquad (1) $$

IV. SIMULATED ROBOT ARM IN 3D SPACE

The intended arrangement of servo motors and links with respective lengths is simulated in MATLAB as in the figure below. Orientation of the base motor corresponds to (0, 0, 0) position of the Cartesian plane. Length of arm when extended to its maximum limits will be nearly 65cm. The degree of the reach of the robot manipulator directly relates with the kinematic structure of the robot arm.

The workspace makes all points the end effector can reach. It should satisfy the requirement of the main service purposes intended to acquire from the manipulator. Tasks performed and arm length were prime concerns during deciding mechanical arrangement of links, control system, power supplies and servo motors. Prior to giving any control signal regarding any end position of the robot, it's important to find whether the system can reach the desired orientation with respect to its mechanical and electrical restraints.

The simulation of the workspace allowed modification or change in the placement or configuration of mechanical parts within the manipulator before setting it up on a floor. MATLAB simulation of the kinematic structure containing the points it can reach in 3D space is depicted below [10].

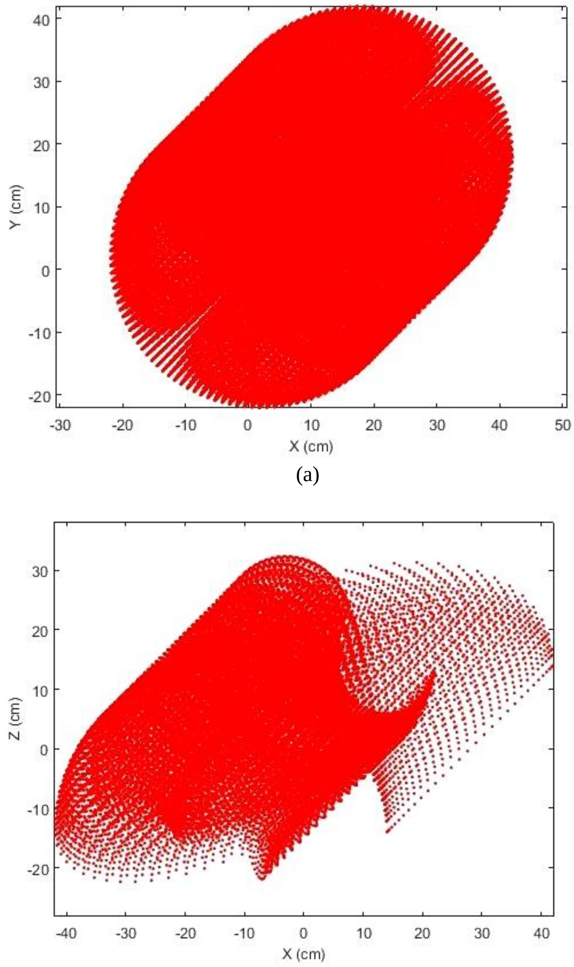

Fig. 3. (a) Workspace in XY plane (b) Workspace in XZ plane

The workspace obtained above are relevant to the degrees of freedom implemented (06), the link lengths (4cm) and motor angle limits [11]. It can be seen that the arm cannot reach all the points in the work envelope. But it is also observed that the arm reach is XY plane is very much higher. Software simulation is the methodology used to assess the feasibility and the optimal performance of the kinematic structure utilized for the design.

V. Trajectory Planning

Positioning of servo motors are obtained through trajectory planning. Shown below is a MATLAB simulation of the dynamic analysis conducted on the base joint prior to the selection of the motors. The time taken to execute the trajectory and beginning and ending zero velocity are the restraints used in the equations.

Cubic polynomial method is used to plan the trajectory from the desired orientation to the final position. Point to point motion is assessed using following cubic polynomial trajectories with the parameters: initial position, final position, initial time and the time of halt as knowns.

Four movements of the robot manipulator are considered to observe angle requirement for the joint motors. The considered movements are as follows.

Movement 1: 0^0 to 90^0
Movement 2: 90^0 to 0^0 (reverse direction)
Movement 3: 30^0 to 60^0
Movement 4: 10^0 to 170^0

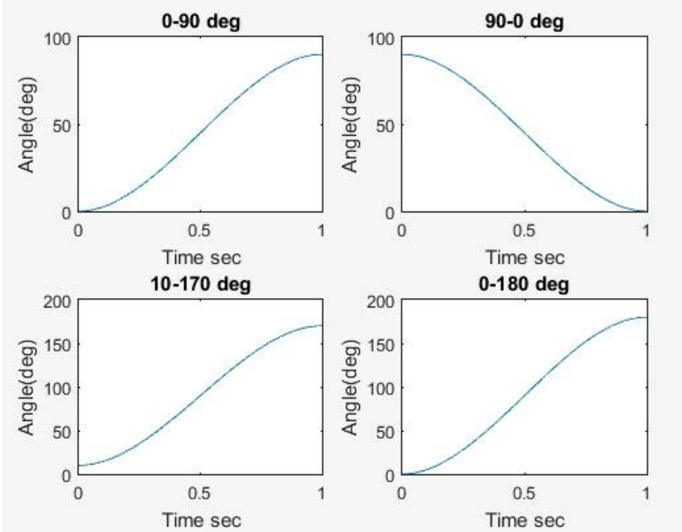

Fig. 4. Angular displacement of the base motor

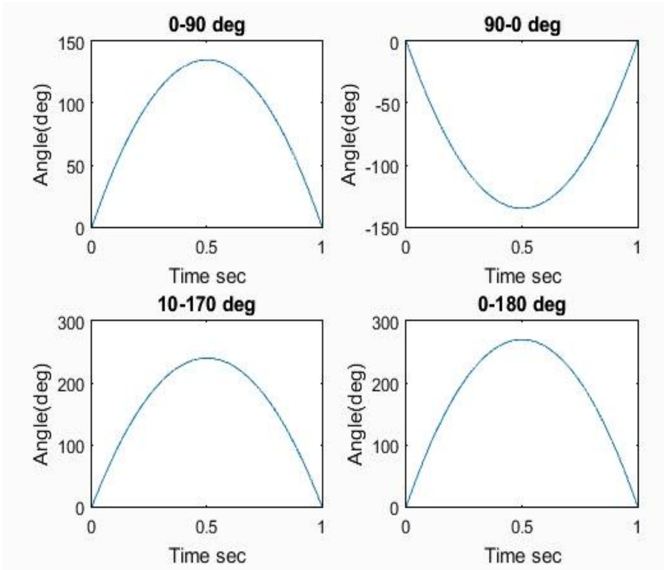

Fig. 5. Velocity profiles corresponding to previously obtained functions

The movements obtained for the above angles are shown in Fig. 4. The corresponding cubic polynomial equations are shown below.

Movement 1: $q_1(t)= 90t^2-60t^3$ (2)
Movement 2: $q_2(t)= 90- 90t^2+60t^3$ (3)
Movement 3: $q_3(t)= 30+ 30t^2-20t$ (4)
Movement 4: $q_4(t)= 10+ 160t^2-106.67t^3$ (5)

Differentiation of the angular displacement gives the following velocity trajectories. The graphs corresponding to the velocity functions are plotted against time in Fig.5 .

Movement 1: $v_1(t)= 180t -180t^2$ (6)
Movement 2: $v_2(t)= -180t+ 180t^2$ (7)
Movement 3: $v_3(t)= 60t -60t^2$ (8)
Movement 4: $v_4(t)= 320t- 320.01t^2$ (9)

VI. Orientation In Space

Trajectories can be planned either in joint space, directly specifying the time evolution of the joint angles or in Cartesian space, specifying the position and orientation of the end frame.

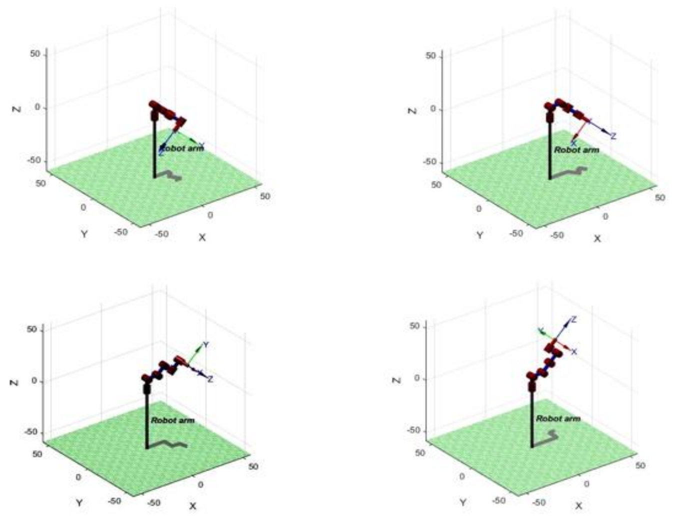

Fig. 6. Simulation of selected positions of the end effector[4]

Issues in trajectory planning include attaining a specific target from an initial starting point, avoiding obstacles within the limits of manipulator capability.

Fig. 6 shows how the end effector is moved when the below motor configurations are given. Here the forward kinematics parameters are given as input so that positioning is easier and faster than calaculation of inverse kinematics.

Movement 1: motor2: pi/4 motor4: -3/4 pi motor5: pi
Movement 2: motor3: pi/4 motor4: -pi/4 motor5: -3/2 pi
Movement 3: motor3:-pi/4 motor4: -pi/2 motor5: 3/5 pi
Movement 4: motor3: -pi/4 motor5: -3/2 pi

VII. Physical Model

It is essential to check the dynamic behavior of a system before it is actually implemented. SOLIDWORKS accelerates the design process, saving time and development costs, and making the product more productive. We have used the very accurate measurements of each and every object that we have designed in order to get the actual torques of motors and for observe real dynamic behavior. Individual components created in that way are shown in Fig. 7.

In order to develop a service robot hand it is required to reach in different positions in different orientations , so that we decided to develop a hand with six degrees of freedom , then also we choose servo motors with a rotation angle limit of 180 degrees , that expands the workspace of the robot arm.

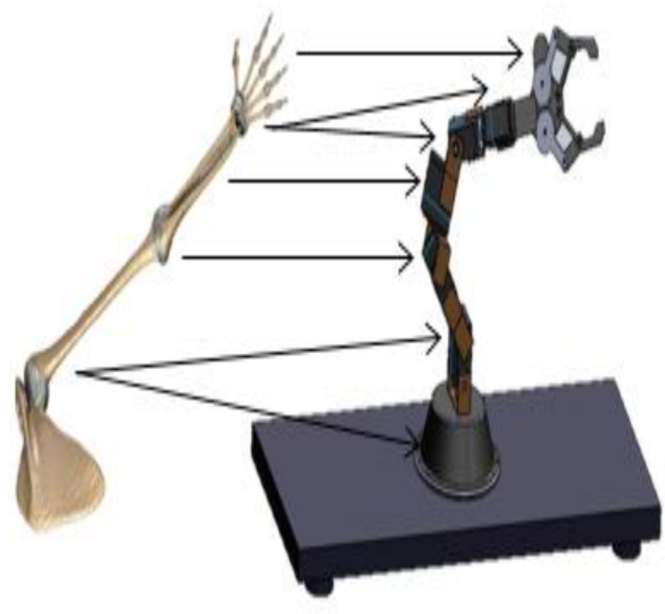

Fig. 8. Structure of the robot arm

Actual behaviour of the robot resembles the motion of the human arm. Such movements corresponding to joints in the human arm are shown in Fig. 8. In physical design it is basically a serial manipulator having all joints as revolute .The arm geometrical configuration is made up of shoulder, elbow and wrist in correspondence with the human arm joints. Each of these joints except the wrist and shoulder has a single DOF. Wrist can move in two planes (roll and pitch), thus making the end-effector more flexible in terms of object manipulation. Constructed in a vertical articulated fashion, the robot offers visual observation of the mechanical behavior of each joint at a glance. The arm is fully-actuated with each DOF achieved by a precise servo motor (equipped with an potential encoder). The end-effector is a three finger gripper having rubber pads, we choose our gripper to have three fingers because we suppose to perform tasks such as pick and place, assisting for a disable, etc. So it is essential to have at least three fingers for handle an object without dropping.

The built in mechanical safety limits restrict the joint motion in case something in the control algorithm goes wrong. As in CAD design, exact rotation limits were used to avoid overturns of motors.

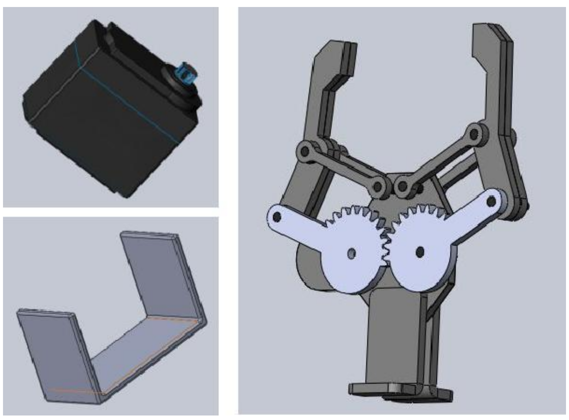

Fig. 7. Components of the arm

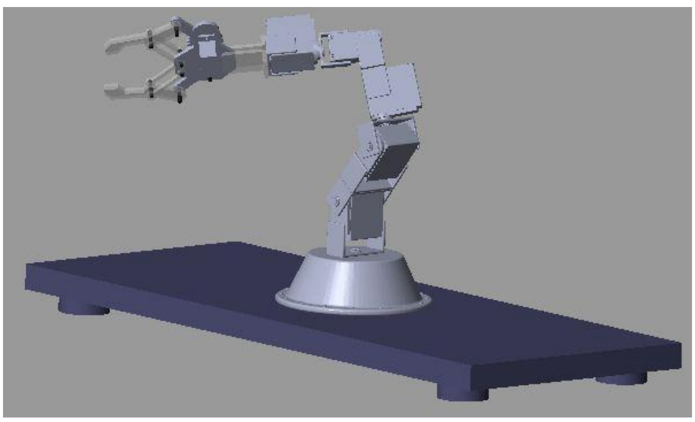

Fig. 9. MatLab model of the overall structure

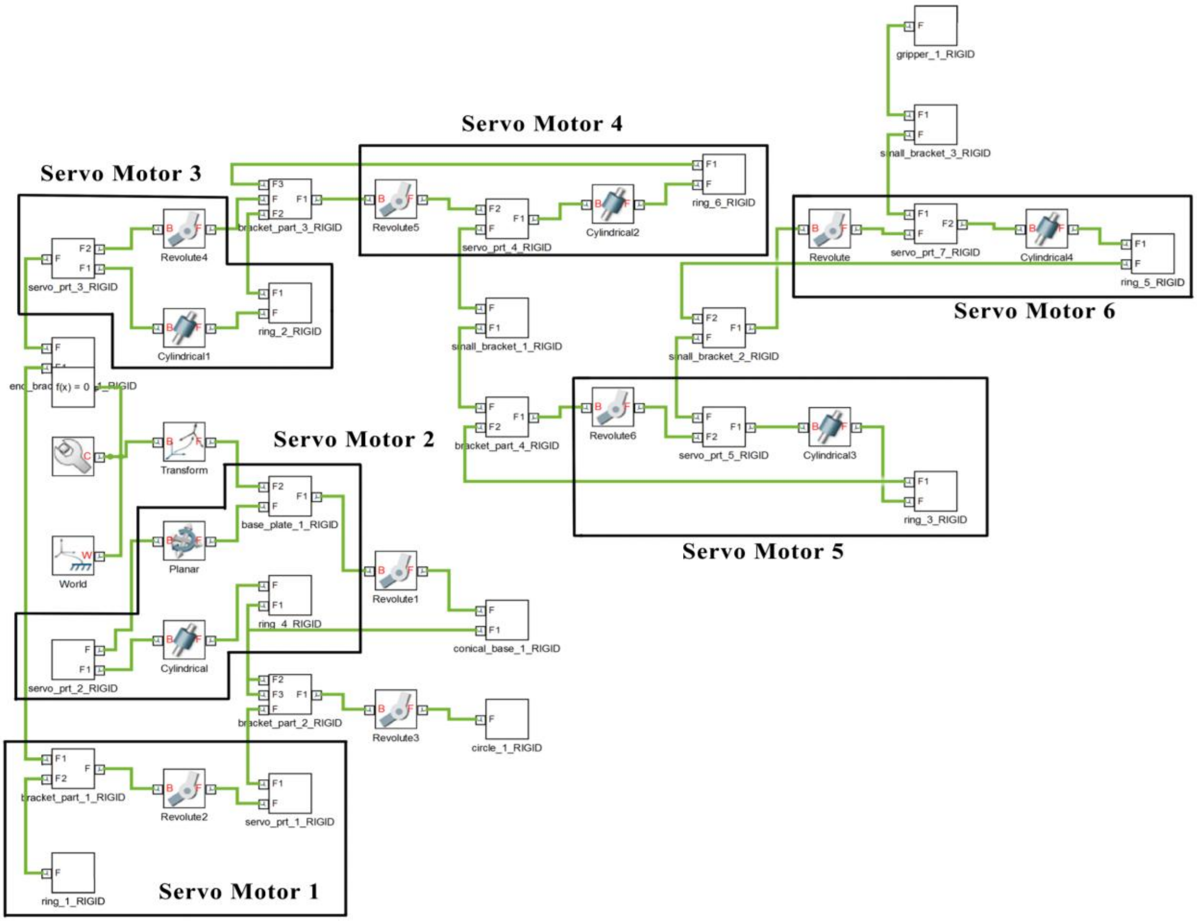

Fig. 10. SimMechanics model of the structure

By using the solid works CAD design MatLab model was created. It is used to get the workspace of the robotic arm and further analyze the dynamic behavior of the robotic arm. Also here this model can be used to virtually simulate the robotic arm while it is in operation by passing the exact parameters of the motors to the matlab model. Then how the arm should behave in that calculated motor parameters can be studied. Fig. 10 shows the simulated structure of the robot arm using SimMechanics.

VIII. Conclusion

The research asseses the feasibility of the present design for the robot arm. Mechanical structure was developed based upon the calculated torques and link lengths. Finally the DH matrix is developed to assess the reach of the robot arm as the arm should reach maximum number of points in 3D space to maximise its performance as a service robot. Forward kinematics analysis showed the workspace which will be sufficient to make the maximum use of the robot. This is because the intention of designing robot is using that for service purposes which will practically need large number of reachable points in 3D space.

Analysis of the outputs of MATLAB simulations shows the workspace , link lengths and angular limits already selected are sufficient for intended activities of the robot arm. Image processing, voice recognition and shapes and colour detection are to be developed in the arm as future improvements.

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