Kinematics And Structural Analysis Of 6 DOF Robotic Arm

Gaurang Kulkarni[1*], Ashwinkumar Mahindrakar[2]

Abstract

Robotic arms in modern times pre-dominantly have a wide variety of applications, from industrial automation to the complexity of human anatomy. A vital component of an automated robotic arm is the ability to learn motions, that is, the ability of the arm to be programmed and its function manipulated by the user. The development of a robotic arm for material handling purpose which will be capable of moving the component from one position to another in an unstructured environment. The robotic arm enables the use of servo motors programmed by the Arduino software to achieve the task. This system prefers out-performing a series of instructions to perform the program each time. In the industrial or the production sector, there are several types of robots that has been fabricated for the storage and servicing of materials and for the dislocation of material from one workstation to another. This type of robot has been quite popular in industries. This study is focused on the research and development of a robotic manipulator. In this paper, the design has been provided along with the kinematic analysis and the structural analysis of the robotic arm. From this paper an investigation is conducted as to how sturdy the structure of robotic arm is and how it can be controlled by an application which will be proven in the result.

Keywords— Design, Kinematic Analysis, Manipulator, Structural Analysis.

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I. INTRODUCTION

In modern times the manipulators are increasingly being sophisticated and condensed in performing commands to substitute human exclusively for monotonous and complicated tasks [1] Traditionally, robots are segregated into two categories: commercial robots and utility robots. The International Robot Federation (IFR) defines service robots as those that operate partially or totally autonomously to perform services that benefit both humans and machines, excluding manufacturing tasks. These robots are currently being used in offices, military operations, medical clinical tasks etc. They also perform specific tasks which includes the implementation of robotic technology in the management of hazardous material, else, by reducing the risk of accidents and health related problems. So, a human could be Replaced by robots to do the task [2]. The robotic arm is a general purpose programmable robotic controller with the features that are comparable to the human arm Joints that enable either rotational (as in an articulated robot) or translational (direct) movement combine such controller assignments. Controller connections are often conceived to form kinematic chains in the system. In the business world, the controller's kinematic chain is known as its end effector and is no different from a human wrist. The end effectors are often designed to perform the ideal job depending on the application. For example, welding, gripping, turning [3].

While humans experience fatigue in harsh environments and become physiologically broken, robots can easily be used without taking into consideration of fatigue (as it runs on a healthy power supply to the robot) and

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process commands without getting impulsive. With the advancement in computer technology and programming, robots are expected to become more sophisticated and follow repetitive tasks and perform them ceaselessly. The robotic arm concept changed the industry [4]. The main ideology in developing robots is to design robots that can be used in everyday life. The advantage of the robot is that it is also important in healthcare, minimizing the risk of human error. Today, robotic manipulators are utilised commercially , manufacturing automobile, architecture, electronics etc. [5] The concept is not new, due to which more study and development are required before robots so that it can be employed in everyday life. Research and studies in circuits, degrees of freedom (DoF), algorithms, programming, metallurgy, and system design are necessary for development of robotic technology [6].

Mohammed Abu Qassem and others [7], They used MATLAB or Simulink tools to test the properties of motion for the AL5B robotic arm. They further applied the forward as well as inverse kinematics in order to develop the robotic models, to solve the path planning problems, and test the robotic arms. Simulation assists in saving the initial investment in the testing process and avoid unnecessary risks. Milind R Shinde and others [8], They formulated the idea of developing a robotic arm to load and unload the material on the lathe machine which underlines the industrial sector. Their goal was to achieve automation and acceleration to improve accuracy and performance. They developed a robotic system simulation that includes visualisation of how the robot moves through its surroundings. CATIA V5 software is used to create a CAD model of the robotic arm, and Workspace Simulation program is used to simulate it. This adds to an increase in total machine productivity through spontaneous operation and full machine usage. Tshseen F. Abaas and Hind H. Abdulridha [9] They proposed a 5 DOF robotic arm model (Lab-Volt 5150) in which they employed DH parameters and tested their robotic arm using the MATLAB application. They have compared the outputs of MATLAB programming and RoboCIM outputs to find the acceptance rate of their robotic arm. Anwar Sabah Ahmed and others [10], In this article, they fabricated a robotic arm controlled by a web page designed by a programming language (HTML). This web page includes a dashboard with controls for moving the servo to the appropriate angle. The receiver side features four servo motors that connect to an Arduino microcontroller that is linked to a wireless home network. One as horizontal arm movement, couple for arm-to-knee motion, and the 4th for grasping objects. They also employed the two ultrasonic sensors to limit the robot arm's reach. Finally, before linking the robot controller to the hardware, use the Proteus programme to simulate it.

Mohammed Naufal Bin Omer [11], They have fabricated a dispositioning robotic manipulator which is directed through software. In this condition, manipulator can only pick up things in specific orientations. A mechanical gripper is employed in this case. As a result, it cannot handle components safely. Objects having a specific alignment will be picked up by the robotic arm, which is determined by the gripper. Ksm Sahari and others [12] In this project, they developed a mechanical model of a SCARA robot which performs a specific task so that it can be used for research and educational purposes. In it, they gave a procedure on how they developed a pick-and-place SCARA robot. After design in third phase of development they have also given inverse and forward kinematics of SCARA robot. Anusha Ronanki and others [13] In this article they have developed a prototype of a robotic arm for library purpose. Their robotic arm consists of gripper which moves in three axis and Atmega eight microcontroller. They have used AVR studio for programming and Protesus software for simulation purpose. Their robotic arm weighs around four kg. R. Jagan and other [14] In this paper they have developed a robotic manipulator for conveyors which can be operated manually as well as through PLC programming software. This robotic manipulator does specific tasks that are provided by the user through PLC program. A. Ajith and others [15] they have introduced a master and slave robotic manipulator “SAKSHA”. It is a manipulator that may be utilised in manufacturing, medical services, and other settings. This controller may replace existing controllers in businesses, making the work easier and more exact. Ashraf Elfasakhany and others [16] In this they have represented the design and development of robot arm that is capable of handling simple tasks for lifting lightweight materials. Mishra et.al [17] and Kruse and others [18] They have studied and built a advanced robotic arm from Arduino Uno using servo motors and potentiometer for picking and placing objects from one workspace to another workspace. Amareswar and others [19] They have developed a robot for armed services. The robot that they have developed detects the incendiary device that passes through metal detector, which also uses camera to see surroundings which is installed in Arduino device.

II. Kinematics of Robotic Arm

A typical configuration of a robotic arm consists of waist, shoulders, elbows, and wrists. All these joints have one DOF each. The Kinematic analysis of the robot provides us with the joint-to-link relationships with the position and orientation of the robotic arm. This was the first introduction provided by Denavit-Hartenberg also known as D-H convention or D-H parameters. These parameters are used for selecting frames of references in robotic applications [20]. In this parameter co-ordinate frames are linked to joints between two links such that one is related with joint [Z] and other to the link [X]. The co-ordinate transformations along a serial manipulator comprises of n connections forms the kinematics equation of robotic arm [20],[21]:

Notations

Z – the respective joint number allotted to the joint

X – the link corresponding to the allotted joint

T is the transformation locating end link.

Equation

$$[T] = [Z_1]\ [X_1]\ [Z_2]\ [X_2] \ldots\ldots\ldots [X_{n-1}]\ [Z_{n-1}] \quad [20]$$

In the equation given in [1]. The number of transformations of the D-H convention is directly related to the degree of freedom associated with the robotic system which is six. And out of these three belong to rotary and the rest of them are translatory motion.

So, the refined equation is

$$[T] = [Z_1]\ [X_1]\ [Z_2]\ [X_2] \ldots\ldots\ldots [X_5]\ [Z_5] \quad [21]$$

There are few rules that are used before finding kinematics solution of a robot and assigning parameters to a robot.

Rule 1: Z_{i-1} is the axis of actuation of joint i.

- *Axis of revolution of a revolution joint.*
- *Axis of translational of a prismatic joint.*

Rule 2: Axis X_i is perpendicular to Z_{i-1}.

Rule 3: Axis Y_i is derived from X_i and Z_i

Generally, while assigning frames to a robot right hand flaming rule is used, the Thumb is Z-axis which points along axis of rotation or (axis of translation for a prismatic joint), Index Finger is X-axis for a base frame is a free choice; constrained for subsequent joints and finally our Middle Finger points Y-axis. Kinematics analysis of a robot is divided in two parts Forward Kinematics and Inverse Kinematics.

A. Forward Kinematics

This kinematic solution is formulated to establish the position and orientation of a robot arm's end effector from a given joint angle. Using DH parameters line diagram of a robots are developed. The robotic arm here used have six DOF and the line diagram is provided in fig.1.

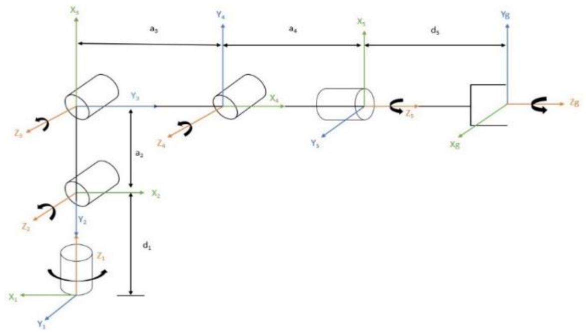

Fig. 1 Line Diagram of Robotic Arm

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In this Line Diagram, Z_1, Z_2, Z_3, Z_4, Z_5 is the axis of rotation of or (axis of translation for a prismatic joint) of each joint.

Zg is the axis of rotation of gripper (End-Effector).

X_1, X_2, X_3, X_4, X_5, X_g are the axis free choice; constrained for subsequent joints.

Table 1. DH parameters of the robotic arm

Link	a_i (mm)	α_i (degree)	d_i (mm)	θ_i (degree)
1	0	90	52	θ_1
2	150	0	0	θ_2
3	110	0	0	θ_3
4	46	0	0	θ_4
5	0	90	64	θ_5
6	0	0	0	θ_6

Here,

The parameters of the DH convention are given: -

$a_i - Link\ length\ of\ Link\ 'i'.$
$\alpha_i - Link\ twist\ of\ Link\ 'i'.$
$\Theta_i - Joint\ angle\ of\ Joint\ 'i'.$
$d_i - Link\ offset, prismatic\ variable.$

The parameters of the D-H conventions are labelled to the system.

Moreover, the transformation matrix between 2 consecutive links can be obtained from assigning DH frame as follows: -

$$Ti = Rz, \Theta i\ Tz, di\ Tx, ai\ Rx, \alpha i$$

$$\begin{bmatrix} c\Theta i & -s\Theta i\ c\alpha i & s\Theta i\ s\alpha i & ai\ c\Theta i \\ s\Theta i & c\Theta i\ c\alpha i & -s\Theta i\ s\alpha i & ai\ s\Theta i \\ 0 & s\alpha i & c\alpha i & di \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where;
$c\Theta i = \cos(\Theta i)$
$s\Theta i = \sin(\Theta i)$
$c\alpha i = \cos(\alpha i)$
$c\alpha i = \sin(\alpha i)$

After putting these values from table 1 in equation (1) and solving it in python we got final transformation matrix as follow

$$\begin{bmatrix} 0 & 1 & 1 & 0 \\ -1 & 0 & 0 & 1 \\ 7 & -1 & 0 & 4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

B Inverse Kinematics

The Inverse Kinematics analysis of a robot is an analysis in which we calculate the angles of joints that will assist the gripper of the robotic arm to move to the desired position. There are two approaches for finding the Inverse Kinematics of the system, first is analytical approach and second is numerical approach. In this context, the analytical approach has been applied for finding the angles of joints.

Here are some of the assumptions that are considered;

- Only the first three joints of the robot arm determine the position of the end effector.
- The rest of the three joints (and all other joints after that) determine the orientation of the end effector.

The rotation matrix of the specified frame can be found through DH parameter approach or analytical approach The rotation matrix of the third frame relative to zeroth frame which is essential in position determination is given: -

$$R_3^0 = \begin{bmatrix} -\sin\theta 2 & 0 & cos\theta 2 \\ \cos\theta 2 & 0 & \sin\theta 2 \\ 0 & 1 & 0 \end{bmatrix} \quad (3)$$

The inverse of the rotation matrix of sixth frame to the zeroth which is essential for the orientation determination of the frame is given as: -

$$R_6^3 = (R_3^0)^{-1} R_6^0 \quad (4)$$

The rotation matrix of the sixth frame to the third frame is given as: -

$$R_6^3 = \begin{bmatrix} -\sin\theta 4 cos\theta 5 cos\theta 6 - cos\theta 4 sin\theta 6 & sin\theta 4 cos\theta 5 sin\theta 6 - cos\theta 4 cos\theta 6 & -sin\theta 4 sin\theta 5 \\ \cos\theta 4 cos\theta 5 cos\theta 6 - sin\theta 4 sin\theta 6 & -cos\theta 4 cos\theta 5 sin\theta 6 - sin\theta 4 cos\theta 6 & \cos\theta 4 sin\theta 5 \\ -sin\theta 5 cos\theta 6 & sin\theta 5 sin\theta 6 & cos\theta 5 \end{bmatrix}$$

(5)

Now, we need to orient the end effector in an order that it defines the rotation matrix for frame 6 relative to frame 0. We can select any rotation matrix. In this we have kept the gripper pointing orthogonal to the surface. Due to this Z_6 will be pointing in the same direction as Z_0 and because of this the X_6 is now oriented in opposite direction as X_0. Similarly, the Y_6 is oriented opposite direction as Y_0.

Thus, the rotation matrix of frame six to frame zero is: -

$$R_6^0 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

III Ansys of Robotic Arm

After performing the kinematic analysis of the robot arm, we established the transformation matrix of the robot arm and the theta value of the arm. ANSYS of a robotic arm is used to determine the amount of stress, strain, and deformation that occurs at every link of the system. This allows us to diagnose the system and check for complications in the design. We used the ANSYS software to find these values. It is a software for calculating the deformation of a part using the finite element method formulation. This software generates a simulation model showing the amount of stress, strain, or deformation occurring in every link of the system. The procedure of achieving this methodology is by importing a Solidworks file of the arm joint to the ANSYS software to determine arm stresses and deformation. After importing the file into ANSYS, we select a material. Materials are an essential factor. The material called the ABS Plastic (shock resistant) is used for this arm. It consists of three monomers: acrylonitrile (it is responsible for the polymer's high chemical resistance and thermal stability), butadiene (which is responsible for the toughness and impact resistance of the ABS polymer), and styrene (which provides the stiffness and strength of

ABS-plastics). These properties make this material increasingly and commercially used in industry for manufacturing parts and 3D printing. Due to its opaque nature, it does not exhibit the properties of a crystalline solid. Some key features of this material are: -
Density: - 1.03e-06 kg/mm^2
Youngs Modulus: - 1628 MPa
Poisson's Ratio: - 0.4089
Bulk and Shear Modulus: - 2978.4, 577.76 respectively.
Tensile Ultimate Strength: - 36.26 MPa
Tensile Yield Strength: - 27.44 MPa
Isotropic Thermal Conductivity: - 0.0001997 W/mm ˚C
While performing the analysis of any robot, we have to check for its primary factor that are total deformation occurring on it while giving some specific load on it. The reason is that total deformation tells us how much an object may deform from its original dimensions or size in the given direction depending upon which deformation we have to measure. The alternate method of determination of load is the stress this tells us the equivalent stress which allows us to graphically display the stress acting on a structure. The von Mises equivalent stress is one of the most commonly used stresses. Equivalent von Mises stress uses the results of simple uniaxial tensile tests to predict the yield strength of the material under multiaxial loading conditions.
In this paper we have provided the structural analysis of all the joints in which the total deformation and unevenly distributed stress occurring on all the links of the robot . After predefining the input values for the analysis of the joints.
The total deformation in the Fig.2 has been segregated into a hierarchy of well-defined zones. These zones comprise of the spectrum which begins with red and concludes with blue. The red zone tells us the maximum deformation that can occur on part when we provide a 999 N torque on it. Similarly, when we go downwards towards blue region the deformation value changes becoming low since blue zone comprises minimum deformation zone.

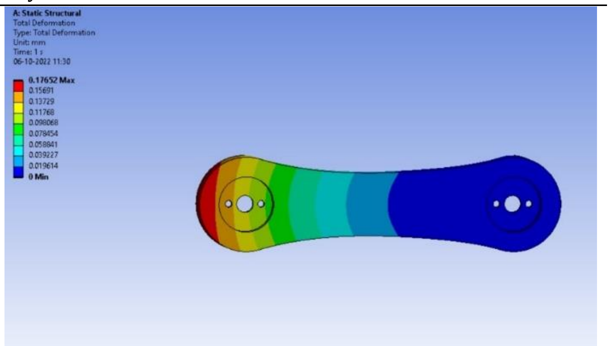

Fig. 2 Total deformation on Arm 1.

In the procedure of finding the solution of the analysis in ASNYS the time taken to deform the link into these colored zones is defined by 2 sec and frames are 20. But this time doesn't tell us the exact zones that occurs in the frames that are generated. The ideal time and frames from the provided options are 40 frames and 4 sec (maximum time and frame in ANSYS is 100 frames and 10 sec). In fig.2 we can see that the time taken to form all zones is 4 sec and the no. of frames which are formed are 40. The zones are divided in 8 parts. These 8 parts gives us the maximum deformation and minimum deformation values. From Fig.2 we can see maximum deformation value at red zone is 0.17652mm, minimum is 0mm at blue zone and average value is 0.0456 mm.
Similarly for all parts same procedure is followed and the images of each and every part is given below:-
From figure 3 we found Total Deformation (max): - 0.0592 mm.
Average Total Deformation: - 0.0007221 mm.
Similarly, Total Deformation (min): - 0 mm.

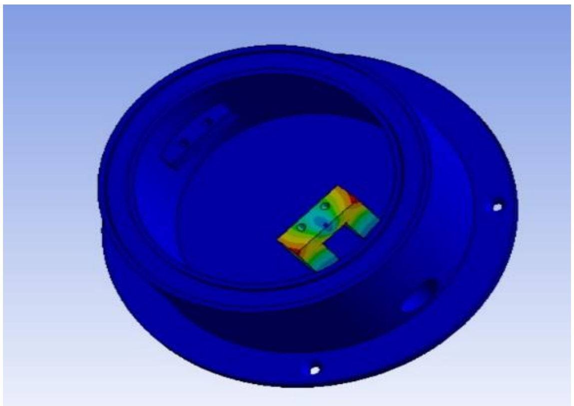

Fig. 3 Total Deformation on Base

From figure 4 we found Total Deformation (max): -0.7989 mm.
Average Total Deformation: - 0.15823 mm.
Similarly, Total Deformation (min): - 0 mm.

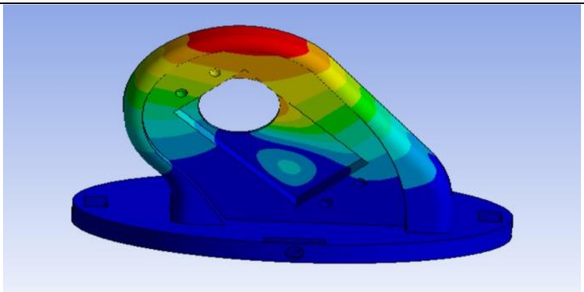

Fig. 4 Total deformation on Waist

From figure 5 we found Total Deformation (max): - 0.11266mm
Average Total Deformation: - 0.036378 mm
Similarly, Total Deformation (min): - 0 mm.

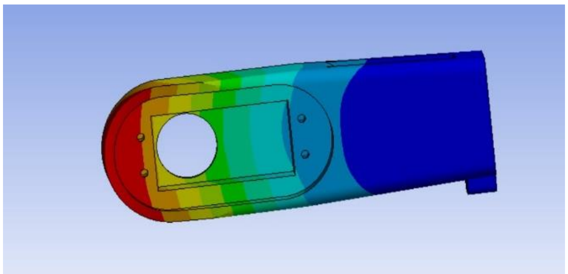

Fig. 5 Total Deformation of Arm 2.

From figure 6 we found Total Deformation (max): - 0.021352 mm
Average Total Deformation: - 0.0034228 mm
Similarly, Total Deformation (min): - 0 mm.

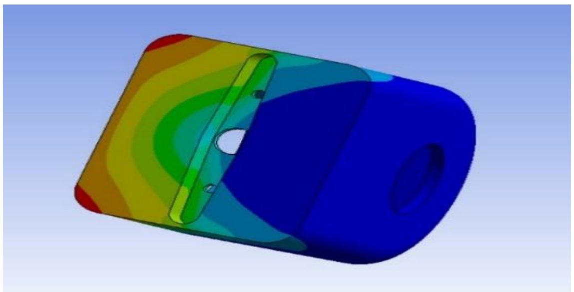

Fig. 6 Total Deformation of Arm 3(1)

From figure 7 we found Total Deformation (max): - 0.06730 mm
Average Total Deformation: - 0.026727 mm
Similarly, Total Deformation (min): - 0 mm.

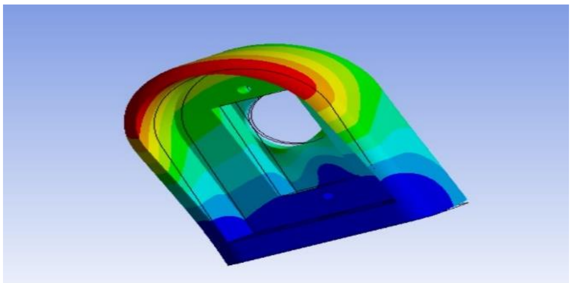

Fig. 7 Total Deformation of Arm 3.

From figure 8 we found Total Deformation (max): - 0.14498 mm
Average Total Deformation: - 0.040131 mm
Similarly, Total Deformation (min): - 0 mm.

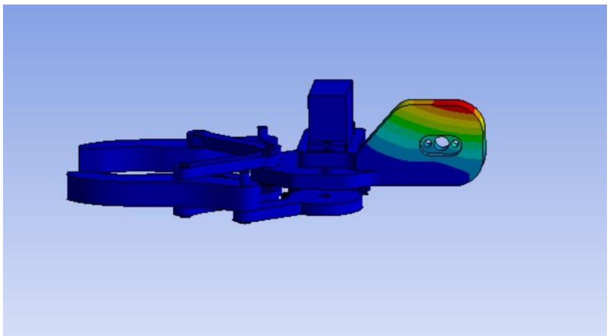

Fig. 8 Total Deformation of Gripper.

IV Experimental Setup

After developing the Total Deformation of every Link, we did experiment to check whether the developed protype works as per given instructions.

A. Technical Parameters

In the given **figure 9** the actual prototype of the robotic arm is illustrated with its technical specifications which are as given below: -

Table 2. Technical Specifications

1	Degree of Freedom (DOF)	6
2	Payload Capacity (Fully Extended)	1000 gm
3	Maximum Reach (Fully Extended)	250 mm
4	Rated Speed (Adjustable)	0 – 0.3 m/s
5	Joint Speed (Adjustable)	0 – 60 rpm
6	Control Software	Computer interface (GUI)
7	Shoulder Base Spin	180°
8	Shoulder Pitch	180°
9	Elbow Pitch	180°
10	Wrist Pitch	180°
11	Wrist Spin	180°
12	Gripper Opening (Max)	80 mm

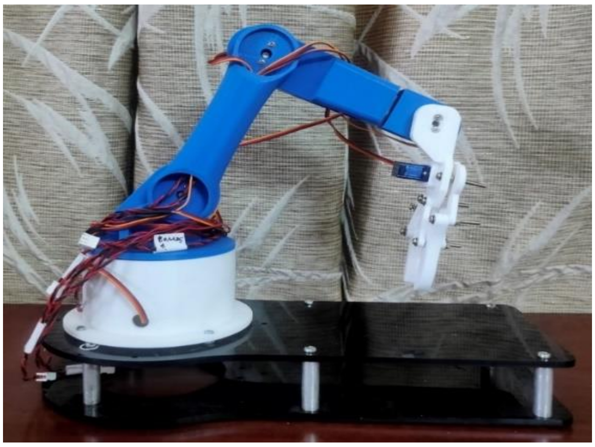

Fig. 9 Actual Prototype.

B. Actual Performance Readings

Table 3. Performance Readings

1	Joint Speed (Adjustable)	0-45 rpm
2	Shoulder Base Spin	170°
3	Shoulder Pitch	140°
4	Elbow Pitch	160°
5	Wrist Pitch	120°
6	Wrist Spin	170°
7	Gripper Opening (Max)	60 mm

After the fabrication of the robot is completed, the next step is the performance evaluation along with the precision and the accuracy validation with pick up and place of desired component from the present location to the preferred destination. For this we developed an environment such that the rotation of the motor can be monitored using a spreadsheet on which the **target, present and the intermediate** location are marked in the form of line segment which are drawn in such a manner that they represent certain angle on the X-Y plane. The objective of the experimental analysis is to achieve the preferable motion which with the manipulator moves to the location with accuracy and precision.

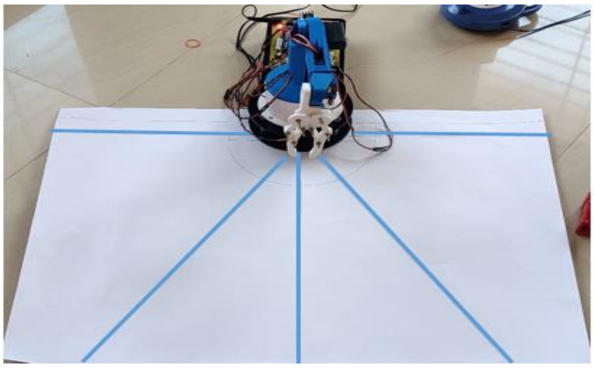

Fig. 10 The intermediate position. it is defined as when the servo motor of the base is at 90 degree or the initial position

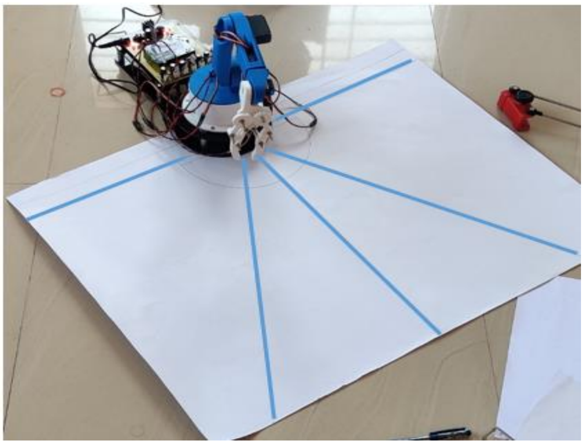

Fig. 11 the initial position, the servo motor of the base is at 30 degrees to the left or can be defined as 60 degrees

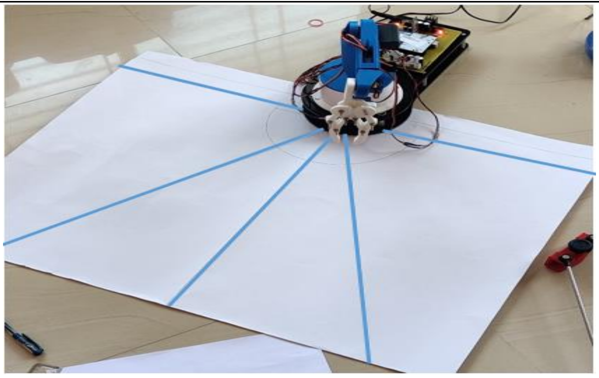

Fig. 12 the final position the servo motor is at 30 degrees to the right or can be defined as 120 degrees

V. Results and Discussion

After performing the experimentation, an application was developed for the dislocation of the manipulator. From figure 13 we can see that slider on the application slides into a position where the shoulder and the waist move into the central position. When we move the slider to the left side, the waist and shoulder's orientation of the robotic arm is shifted to the left side from where it picks the object by extending its shoulder as shown in figure 15. When the object is picked the shoulder is retraces its step back and the waist slider is moved to the right side so that it can place the object at a new location as seen in figure 17.

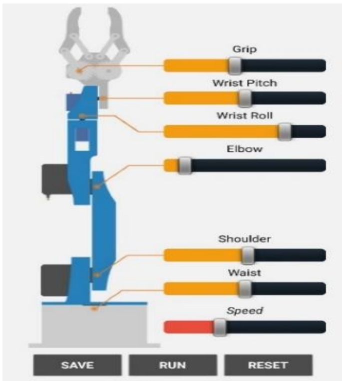

Fig. 13 The initial slider position of waist and shoulder

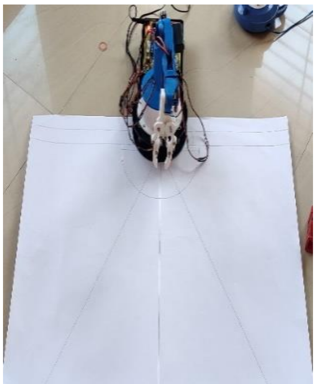

Fig. 14 The initial position of Robotic Arm

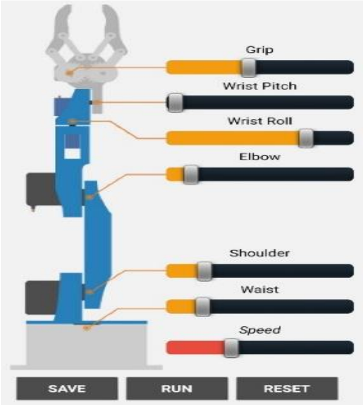

Fig. 15 The slider of waist and shoulder towards left

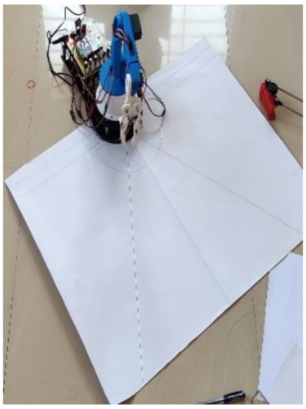

Fig. 16 The orientation of Robotic Arm towards left

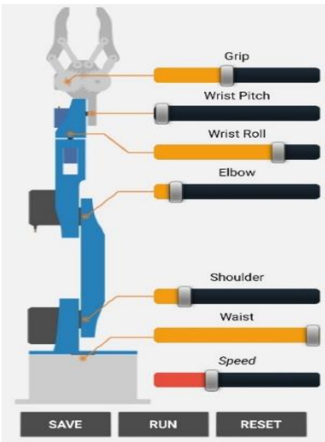

Fig. 17 The slider position of waist towards right

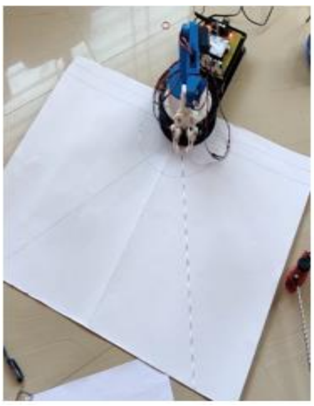

Fig. 18 The orientation of Robotic Arm towards right

VI. Conclusion

This article depicts the design and structural analysis of a Robot Manipulator that moves an object from its present place to its goal. Structural research suggests that the robotic arm is appropriate for small-scale enterprises where lifting weight is limited. This work resulted in the development of an application interface for robotic arm pick and place that is both accurate and user friendly.

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