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Design and Development of a Low-Cost Arduino-Based Robotic Arm for Industrial Applications

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Abstract— Robots are machines designed to perform various tasks repeatedly with high precision and efficiency, thereby reducing human involvement in hazardous, repetitive, and labour-intensive operations. Robotic arms are widely used in industrial applications such as pick-and-place operations, material handling, firefighting, and other automated tasks. In this study, a low-cost robotic arm is developed using servo motors, lightweight acrylic material for the arm structure, and an open-source Arduino microcontroller for controlling the servo motors according to the programmed sequence of operations. A lead-through programming approach is incorporated to simplify task programming and enable users to program the robotic arm for specific applications. Various design and simulation software tools are used for the modelling, analysis, and evaluation of the robotic arm. Since conventional industrial robots are relatively expensive, the primary objective of this work is to develop a cost-effective robotic arm that can be made accessible for educational and small-scale industrial applications. Finite Element Analysis (FEA) is performed to evaluate the structural behaviour of the robotic arm and to identify the regions experiencing maximum stress under the specified loading conditions. The analysis results provide useful insights into the structural performance and potential critical regions of the proposed robotic arm.

Keywords— Robotic Arm, Arduino, Servo Motor, Lead-Through Programming, Stress Analysis, Acrylic Material.

1 Introduction

In today's industries, most factories use automated robots to perform production activities, particularly in the field of industrial automation. Robotic arms are widely used for applications such as welding, material handling, thermal spraying, painting, drilling, pick-and-place

operations, and other repetitive manufacturing tasks [8], [14], [23]. The development and application of robotic arms have been extensively studied for industrial and educational purposes [3], [7], [15].

Although many robotic products are available in the market, conventional

industrial robotic systems can be relatively expensive and bulky for educational and small-scale applications. Therefore, several researchers have investigated the development of low-cost robotic arms using open-source controllers, servo motors, and simplified mechanical structures [1], [7], [10], [20]. Arduino-based robotic systems have also been investigated for controlling robotic arm movements and implementing different programming approaches [1], [10], [13], [24].

Many existing robotic arms are designed for specific applications and may require dedicated programming and control systems. Low-cost and reconfigurable robotic arms can provide greater flexibility for educational, research, and small-scale industrial applications [1], [2], [7]. Therefore, the present work focuses on the design and development of a low-cost, lightweight, and user-friendly robotic arm using servo motors and an Arduino-based control system.

In addition to the mechanical design, structural analysis of the robotic arm is important for determining the stresses and deformation developed under different loading conditions. Finite Element Analysis (FEA) has been widely used for evaluating the structural performance and optimizing robotic manipulators [4], [6],

[11], [12]. Therefore, the present study also investigates the stress distribution and deformation of the proposed robotic arm under specified loading conditions.

2. Mechanical Design

2.1 Introduction

The mechanical design of the robot arm is based on a robot manipulator with similar functions to a human arm. The links of such a manipulator are connected by joints allowing rotational motion and the links of the manipulator is considered to form a kinematic chain. The business end of the kinematic chain is called the end effector or end-of-arm tooling, which performs the required task [3], [15]. The Free Body Diagram (FBD) is used for the mechanical design and load analysis of the robotic arm. In the present design, the end effector is not included in the structural design because a commercially available gripper is used. This approach simplifies the design and reduces the overall manufacturing complexity and cost of the robotic arm [1], [20].

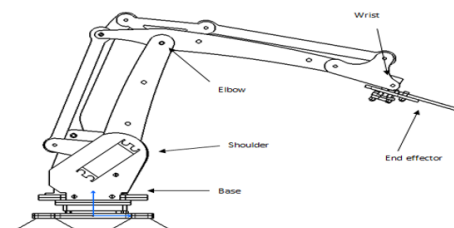


Fig.1. Two Dimensional Diagram of Robotic Arm.

2.2 Robotic Arm Mechanism

Kinematics in robotics is the science of motion investigation. Robot arm links can be rotated or offset according to the reference coordinate frame. Angular and linear displacements between limbs are called joint coordinates and are defined by limb variables. If the coordinates of the end point are given, limb variables can be obtained by going backward. These operations are called inverse kinematics and if the lengths of arm are fixed we can able to find the position of end point in the workspace. This operation is called the forward kinematics. This approach simplifies the design and reduces the overall manufacturing complexity and cost of the robotic arm [1], [20].

2.3 Forward Kinematics

Forward kinematics is the method used to determine the position and orientation of the end effector from the known joint angles and link lengths of a robot arm. The end-effector coordinates can be determined when the link lengths and corresponding joint angles are known [3], [15].

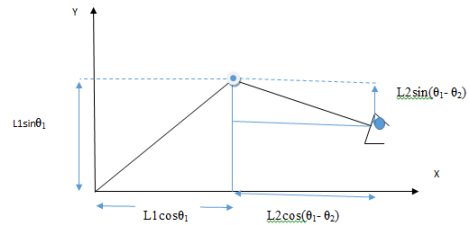


Fig. 2. Forward Kinematics.

Consider a two-dimensional two degree of freedom robot arm as shown in above figure

$L1$ = Length of link 1

$L2$ = Length of link 2

$\theta1$ = angle made by link 1

$\theta2$ = angle made by link 2

$P(x, y)$ = Position of the end effector in space.

X-components

$$X = L1 \cdot \cos \theta1$$

$$X = L2 \cdot \cos (\theta1 - \theta2)$$

Adding above x-components, we get

$$X = L1 \cdot \cos \theta1 + L2 \cdot \cos (\theta1 - \theta2)$$

Y-components

$$Y = L1 \cdot \sin \theta1$$

$$Y = L2 \cdot \sin (\theta1 - \theta2)$$

Adding above y-components, we get

$$Y = L1 \cdot \sin \theta1 + L2 \cdot \sin (\theta1 - \theta2)$$

2.4 Inverse Kinematics

Inverse kinematics is the reverse process of forward kinematics. In this method, the desired position and orientation of the end effector are specified, and the required joint angles are determined to achieve the desired position [3], [15].

2.5 Homogeneous Transformation

The motion of a robot can involve rotational and translational transformations. These transformations can be mathematically represented using homogeneous transformation matrices. A homogeneous transformation matrix provides a

convenient method for representing the position and orientation of robotic links and end effectors [3], [15].

$$H = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Translatory transformation

The homogeneous translatory transformation is represented by the following matrix

$$h(transa,b,c) = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Rotational transformation

The homogeneous rotational transformation matrix is represented by the following matrix

Rotation about x-axis

$$h(rot,x,\theta) = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & \cos \theta & -\sin \theta & b \\ 0 & \sin \theta & \cos \theta & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Rotation about y-axis

$$H[rot(y,\theta)] = \begin{bmatrix} \cos \theta & 0 & \sin \theta & a \\ 0 & 1 & 0 & b \\ -\sin \theta & 0 & \cos \theta & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Rotation about z-axis

$$H[rot(z,\theta)] = \begin{bmatrix} \cos \theta & -\sin \theta & 0 & a \\ \sin \theta & \cos \theta & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

2.6 Load Calculation

The first step is to label your FBD, with the robot arm stretched out to its normal position.

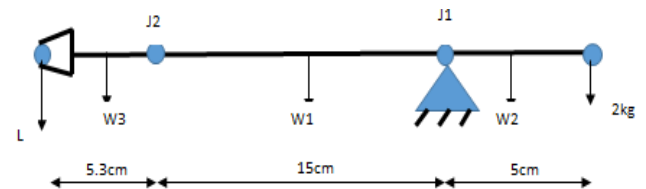


Fig. 3. Free body diagram of link

For moment arm calculations, multiplying downward force times the linkage lengths. This calculation is must be done for each lifting actuator. this particular design has just two DOF that requires lifting, and the center of mass of each linkage is assumed to be length/2.

L1=15cm (length of link 1)

L2=5cm (length of link 2)

L3=5.3cm (length of link 3)

$W1=0.026$ kg (weight of link 1)

$W2=0.004$ kg (weight of link 2)

$W3=0.026$ kg (weight of link 3)

Taking moment at J1

$$\begin{aligned} \sum M &= (W1*(L1/2)) + (W1*L1) \\ &+ (W3*(L1+L3/2)) + (F*(L1+L3)) - \\ &(W2*L2/2-(2*L2)) \\ &= (0.026*15/2) + (0.026*15) \\ &+ (0.027*(15+5.3/2)) + (20.3F) - (0.004*2.5) \\ &-(10)0.195+0.39+0.47+20.3F=10.01 \end{aligned}$$

$$F=0.440 \text{ Kg}$$

Load calculation at extreme position

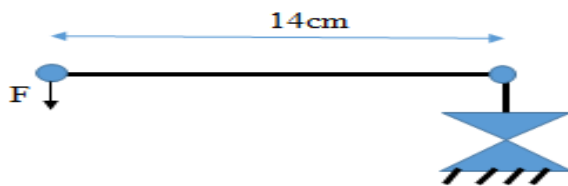


Fig. 4. Free body diagram of link

$$\begin{aligned} \text{Torque} &= \text{Force} * \text{perpendicular distance} \\ 10 &= F * 14 \\ F &= 0.714 \text{ kg} \end{aligned}$$

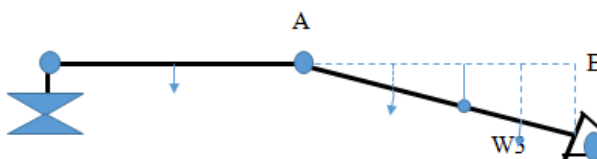


Fig. 5. Free Body Diagram of Maximum Position

$W1=0.015*2=0.030$ (weight of the link 1)

$W2=0.013*2=0.026$ (weight of the link 2)

$W3=0.027$ (weight of the link 3)

To find the perpendicular distance consider the triangle ABC

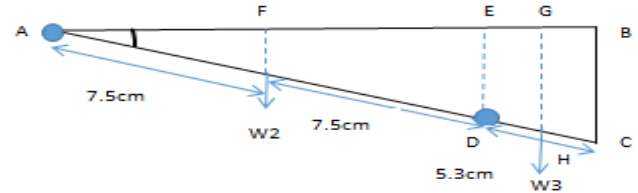


Fig. 6. Free Body Diagram of robotic arm

By using trigonometric functions

$AF=6.74\text{cm}$, $AG=15.86\text{cm}$ & $AB=18.24\text{cm}$

Now,

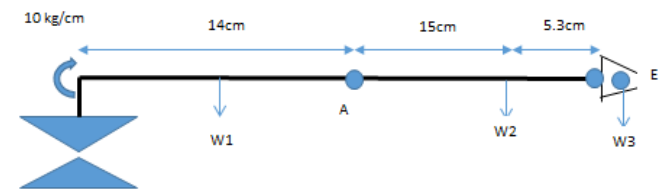


Fig. 7. Free Body Diagram

Torque= Force * perpendicular distance

$$\begin{aligned} 10 &= (w1*(14/2)) + (w2*(14+(15/2))) \\ &+ (w3*(14+15+(5.3/2))) + (L*(14+15+5.3)) \\ 10 &= (0.030*7) + (0.559+(0.854) + (34.3L)) \\ 18.377 &= 34.3L \end{aligned}$$

$$L=0.244\text{kg}$$

So, from above calculations robot can able to pick the load of 244 gm at its extreme point.

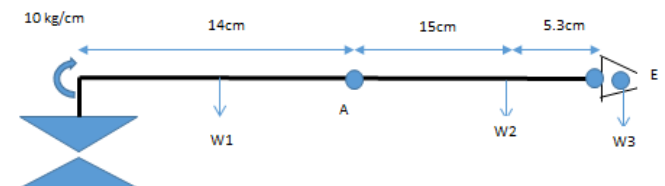


Fig. 8. Free Body Diagram

3 FEM ANALYSIS

3.1 CAD Model of Robotic Arm

The 3D modelling of the robotic arm and its components was carried out using CATIA

V5 software. CAD-based modelling is widely used in the development and analysis of robotic manipulators because it enables accurate representation of the geometry before fabrication [8], [11].

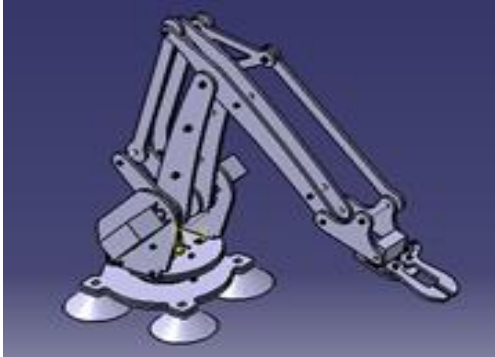


Fig. 9. CAD Model of Robotic Arm

3.2 Material Property

The robotic arm is fabricated using lightweight acrylic material. The material properties used for the finite element analysis are density, Young's modulus, Poisson's ratio, bulk modulus, shear modulus, tensile yield strength, and compressive yield strength.

Density: 1.18 kg/mm³

Young's Modulus: 2800 MPa

Poisson's Ratio: 0.35

Bulk Modulus: 3111.1 MPa

Shear Modulus: 1037 MPa

Tensile Yield Strength: 69 MPa

Compressive Yield Strength: 124 MPa

3.3 Element type

The finite element model was developed using the SOLID186 element. SOLID186 is a higher-order three-dimensional 20-node solid element suitable for modelling structural components and complex three-dimensional geometries. Similar finite element approaches have been employed for structural analysis and optimization of robotic manipulators [4], [6], [11], [12].

Element Type: - SOLID186

Element Shapes: - Quadrilateral

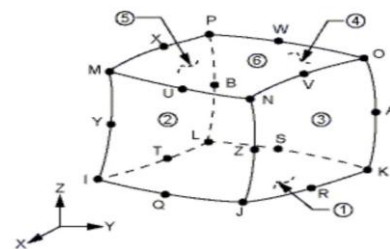


Fig. 10. Solid186 Homogeneous Structure Geometry

SOLID186 is a higher order 3D 20 Node Solid element that exhibits quadratic displacement behavior. The element defines by 20 Nodes having three degrees of freedom per node, translations in nodal X, Y, Z directions. The element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and strain

capability. It also has mixed formulation capability for simulating deformation of nearly incompressible elastoplastic material, and fully incompressible materials.

3.4 Load cases & Analysis Result

Structural analysis was performed by applying the specified loads at the corresponding locations of the robotic arm while constraining the arm at the selected mounting holes. The objective of the analysis is to determine the deformation and stress distribution under the applied loading conditions.

FEA-based structural analysis is commonly used to identify critical stress regions, evaluate deformation, and assess the structural performance of robotic arms and manipulators [4], [6], [11], [12].

In the following structural analysis, have implemented two loads, that is 4N and 9.81N. Following pictures shows the total deformation and the stresses generated with 4N at right end and 19.62 N at left end. Fixed at bottom hole which is 5cm from left hand side.

No of Nodes: - 937

No of Elements: - 107

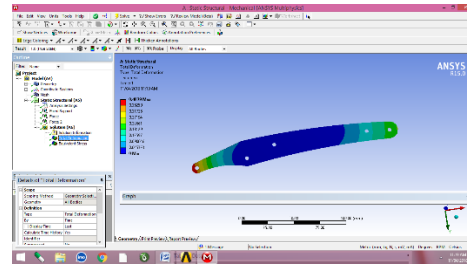


Fig. 11. Upper Arm deformation at 4N

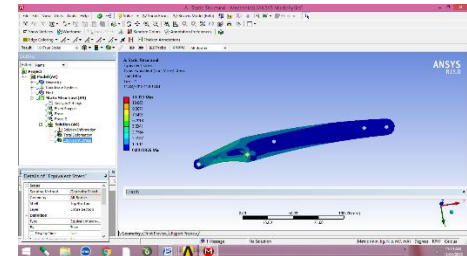


Fig. 12. Upper Arm stress generation at 4N

Following pictures shows the total deformation and the stresses generated with 4N at right end. Fixed at right side hole.

No of Nodes :- 1092

No of Elements :- 133

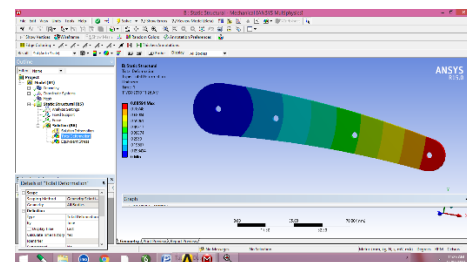


Fig. 13. Lower Arm deformation at 4N

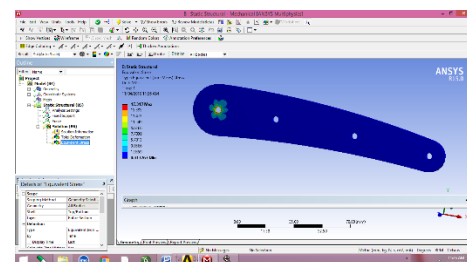


Fig. 14. Lower Arm stress generation at 4N

Following pictures shows the total deformation and the stresses generated with 9.81N at right end and 19.62 N at left end. Fixed at bottom hole which is 5cm from left hand side.

No of Nodes: - 937

No of Elements: - 107.

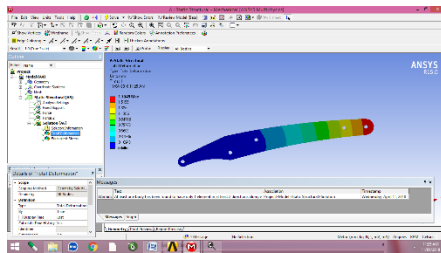


Fig. 15. Upper Arm deformation at 9.81N

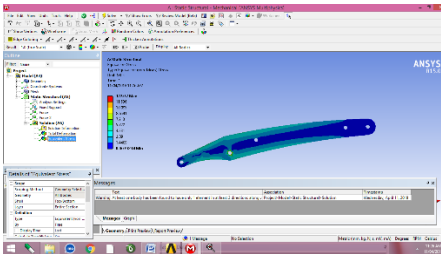


Fig. 16. Upper Arm stress generation at 9.81N

Following pictures shows the total deformation and the stresses generated with 9.81N at right end. Fixed at right side hole.

No of Nodes :- 1092

No of Elements :- 133

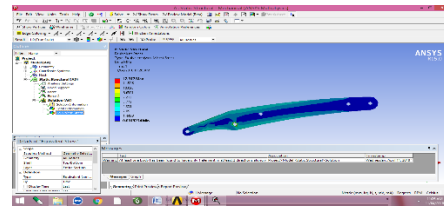


Fig. 17. Lower Arm deformation at 9.81N

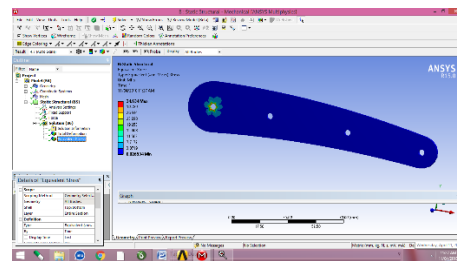


Fig. 18. Lower Arm stress generation at 9.81N

3.5 Result

The FEA results obtained for the upper and lower arms under the specified loading conditions are presented in Table 1

Sr. no	Arm	Applied force at right end	Stress		Deformation	
			Max (MPa)	Min (MPa)	Max mm	Min mm
1	Upper arm	4N	11.323	0.003387	0.4079	0
		9.81N	12.977	0.007923	1.7049	0
2	Lower arm	4N	17.317	0.013262	0.8895	0
		9.81 N	34.634	0.026534	1.7718	0

The results indicate that the maximum deformation observed in the analysed members is approximately 1.77 mm under the considered loading conditions. The maximum stress obtained for the lower arm is 34.634 MPa at an applied load of 9.81 N.

4 Conclusion

From the design and analysis of the robotic arm, it can be concluded that a lightweight, compact, and user-friendly robotic arm has been developed for light-duty applications. The integration of Arduino and servo motors provides a relatively simple, economical, and programmable control system for the required robotic movements.

The Finite Element Analysis (FEA) results indicate that the proposed structure experiences acceptable stress and deformation under the considered loading conditions. The analysis provides useful information regarding the structural behaviour of the arm and the regions subjected to higher stress and deformation, thereby supporting the suitability of the proposed design for the specified operating conditions.

The developed system demonstrates the feasibility of a low-cost robotic arm for educational, research, and selected small-scale automation applications. Its simple construction and programmable control

system provide a suitable platform for studying robotic kinematics, servo motor control, and automation. Further improvements may focus on increasing payload capacity, positioning accuracy, workspace, and structural efficiency through design optimization, improved end-effectors, additional sensors, and advanced control methods.

Overall, the proposed robotic arm provides a practical foundation for further development of economical and flexible robotic systems for light-duty automation applications.

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