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EXPERIMENTAL AND FEA OF ARTICULATED ROBOT ARM FOR ELECTRICAL SCREW ASSEMBLY PROCESS

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ABSTRACT:
Automation is driving a significant transformation in the industrial sector by enhancing productivity, improving skills, ensuring quality, and reducing both manpower requirements and production time. Our project mainly deals around the electrical terminal screw assembly operation, where the screwing is done manually with a screwdriver. Screw ranges from M4 to M8 with variations in screw head. Our challenge is designing a robot articulated arm for performing screwing operations using an electrical screw-driver. We conducted an in-depth review of research papers and articles to explore advanced technologies employed in similar operations across various industries. Based on this analysis, we carefully selected and optimized arm mechanisms to ensure efficiency and effectiveness. Worker process operation output and hand movements considered for designing articulated arms. How workers facing fatigue due to manual operation considered and studied during designing articulated arm. This arm has improvement scope in motorized control. End effector we used is a torque adjustment electrical screwdriver. End effector position always needs vertically with variations in height and area of working. Here we used Solid Works for designing and model analysis.
Keywords: Articulated Arm, Kinematics, Electrical Terminals, Screw Assembly, Matrix Analysis, FEA Analysis of Arm

INTRODUCTION:
Industrial robot applications have experienced significant expansion in both quantity and diversity. The configuration of these robots is gradually shifting from traditional cartesian and cylindrical coordinate systems to articulated designs [1]. This transition is primarily attributed to the enhanced flexibility and versatility offered by articulated robotic arms [2] & [3]. Robotics applications are extensively utilized across various domains, including research, laboratory work, and industrial settings, where they automate processes [4] and mitigate human error. This project focuses on the design of a robotic arm's mechanical assembly, which is typically employed to hold objects during industrial operations [5]. A pertinent example is the use of such an arm to operate a torque-controlled electric screwdriver, vacuum cups, grippers in manufacturing environments [6]. Automating these processes offers numerous benefits, including enhanced productivity among lower-skilled workers compared to their higher-skilled counterparts [7]. Additionally, it significantly reduces error rates and alleviates human fatigue caused by repetitive tasks [8]. The project also focuses on implementing a robotic arm equipped with switching controls. Its force-controlled functionality is especially valuable in industrial and manufacturing settings, where precision and accuracy are of utmost importance [9].
Articulated robotic arms encounter inherent challenges, including the nonlinear relationship between the end effector's position and orientation and the rotational angles of the joints [10]. Additionally, the existence of singular points within the joint state space poses a critical issue, as these points can restrict

the robot's degrees of freedom and operational flexibility [11]. While it has been posited that redundant robotic arms can alleviate singularity issues and enhance operational flexibility, experimental findings demonstrate the utility of redundancy in trajectory control, particularly in environments with obstacles [12]. As the integration of industrial robots into various manufacturing processes continues to rise, the demand for robots that are both flexible and versatile has intensified. Articulated robotic arms, characterized by their rotational joints, have gained prominence due to their potential to meet these evolving requirements [13].

LITERATURE:

The study of articulated robotic arms has been extensively explored in the fields of automation, manufacturing, and precision assembly. Finite Element Analysis (FEA) is a crucial tool for evaluating the structural integrity and performance of robotic arms used in screw assembly applications. Various researchers have contributed to this domain, analysing different aspects such as kinematics, stress distribution, and optimization of design parameters.

Yaniel Torres, Sylvie Nadeau, Kurt Landau [16] present a classification and quantification of human errors in manufacturing, specifically in complex manual assembly. Their research highlights the critical need for understanding and mitigating human errors to improve efficiency and manufacturing defects. The study utilizes applied sciences methodologies to analyse human interactions in production environments.

Zhang, Su, and Chen [17] investigate electrical fires by analysing glowing contact phenomena. Their experimental research and modeling efforts focus on the heat intensity and thermal hazards associated with electrical failures, contributing valuable insights into fire prevention and electrical safety in industrial applications.

Xingyu Qiu [18] examines the forward and inverse kinematics of a 3-DOF RRR manipulator, providing a mathematical framework for robotic arm movements. This work is crucial in developing precise and efficient robotic control systems for industrial automation.

Douglas Thorby [19] explores structural dynamics and vibration in practice, offering a fundamental understanding of dynamic behaviour in mechanical systems.

İrsel [20] extends this study by researching electrical strain gauges and experimental stress analysis, applying a full Wheatstone bridge configuration to enhance measurement accuracy in stress evaluations.

Katal and Gupta [21] present a study on the design and operation of synchronized robotic arms, emphasizing the importance of coordination in robotic mechanisms.

Patidar and Tiwari [22] survey robotic arm parameters, providing a comparative analysis of various robotic arm designs and control methodologies.

Jadhav, Kale, and Kukade [23] discuss the design and manufacturing of robotic arms for industrial applications, focusing on improving efficiency and adaptability in automated processes. Wang and Fengfeng Wang,Yechen Fan [24] investigate the structural design and analysis of a picking robot arm using parallel grippers, offering insights into optimizing gripping mechanisms for industrial use.

Ubeda, Gutiérrez Rubert, and Stanisic [25] contribute to sensor technology in robotics by designing and manufacturing an ultra-low-cost custom torque sensor. Their research enhances robotic precision and control through affordable yet effective sensor technologies.

PROBLEM DETAILED STUDY:

Brasses are copper-zinc alloys widely utilized in electrical applications due to their advantageous physical properties, particularly their electrical conductivity [14]. Screw assembly process is done manually using screwdrivers. Screw fastening assembly with specified torque facing difficulties to achieve consistent productivity using manual process with holding screwdrivers [15]. Soft material screw assembly with loose tool handling and stripping causes damaging of screw heads [16]. Loose or

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low torque electric assembly causes heat generation and leakages [17]. Customized design of articulated arm which holds screwdriver or equivalent tools used for assembly process. Also, it can be used for multiple applications related to the assembly process. Reduction of assembly cycle time and assembly cost using Articulated Robot Arm. Detail of existing assembly process cycle time fig no.1 with part number. Required tightening torque is from 3 to 4 Nmm. As shown in fig no.2 is existing manual assembly station work area

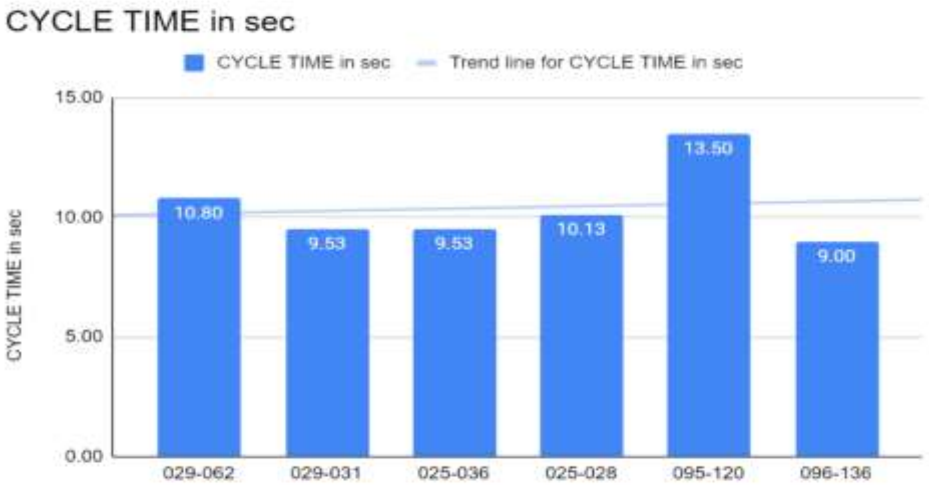

Fig.1 Screw Assembly Cycle Time in sec with part numbers.

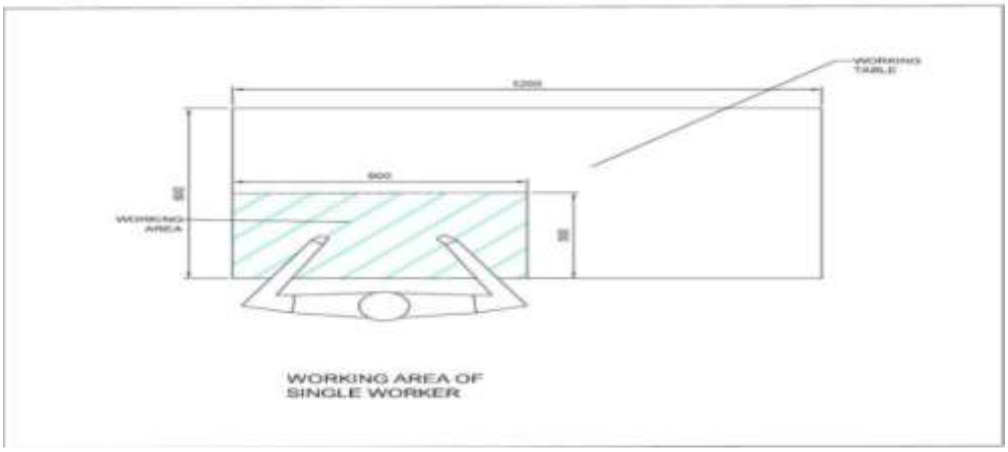

Fig.2 Working area of assembly station.

Here we are considering the work area of the articulated robot arm for covering the existing work area of 2 stations fig no.3, so the arm is suitable for bigger size assemblies.

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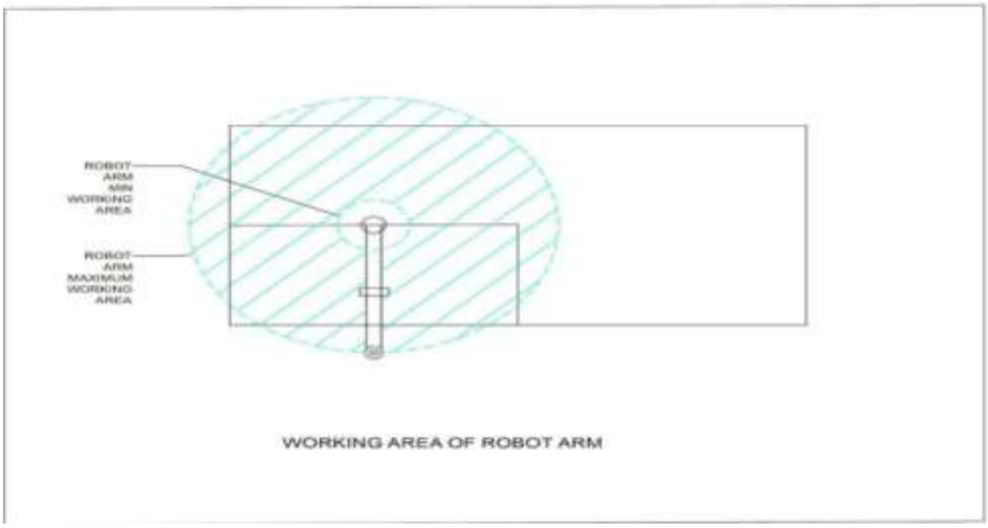


Fig.3 Work area of Articulated Arm with improved working space

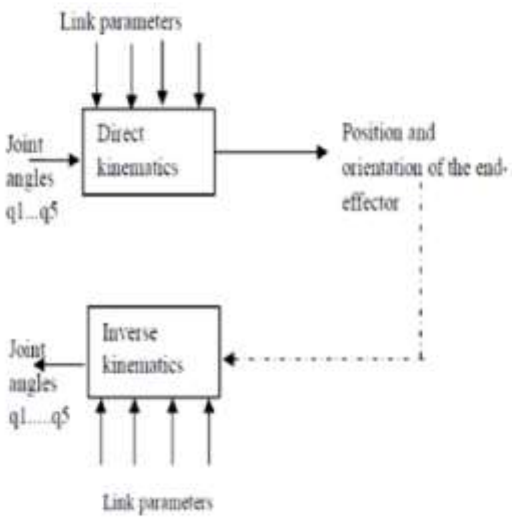
KINEMATICS :

2.2.1 Forward Kinematics:

Forward kinematics for an articulated robotic arm focuses on calculating the position and orientation of the end effector using the given joint parameters, such as angles and link lengths. This process involves the application of transformation matrices, which represent the relative positions and orientations of each joint with respect to a fixed base frame. These matrices are sequentially multiplied to derive the final pose of the end effector in the workspace.

2.2.2 Inverse Kinematics:

Inverse kinematics involves determining the joint angles needed to position the end effector at a specified location and orientation fig no.4. This calculation can be challenging due to the possibility of multiple solutions or configurations for the same end-effector pose.



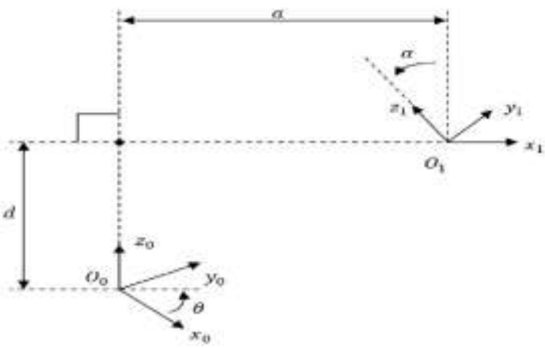


Fig.4 Work area of Articulated Arm

Fig.5 Multi Coordinate frame system

FORWARD KINEMATICS MATRIX:

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Here four parameters are used in D-H parameter representation. All parameters describe the relative rotation and translation between consecutive arm frames fig no 5. Link length (ai): the distance between the axis z0 and z1, and this distance measure along the x1 axis. (Trans, x, ai).Link offset (di): distance from origin O0 to the intersection of the x1 axis with z0 measured along the z0 axis (Trans, z, ai).Joint angle (Ɵi): angle from x0 and x1 measured in plane normal to z0 (ROT, z, Ɵi). Link twist (αi): angle between Z0 and Z1, measured in plane normal to X1 axis (ROT, x, αi).$T_{o\text{-}ee}$ is the equation of forward kinematics for RRR manipulator. Using this equation, we found the end effector position with axis [x,y,z] and orientation [R] .Substituting joint parameters θ1, θ2 and θ3 into the equation $T_{o\text{-}ee}$ gives the final matrix equation[18].

$$
\begin{array}{c}
\text{Orientation} \qquad\qquad\qquad\qquad \text{Position} \\
T_{o\text{-}ee} = \begin{bmatrix} C_1 & -S_1C_2C_3+S_1S_2S_3 & S_1C_2C_3+S_1S_2S_3 & L_3(-S_1C_2C_3+S_1S_2S_3)-S_1C_2L_2 \\ S_1 & C_1C_2C_3-C_1C_2C_3 & -C_1C_2C_3-C_1C_2C & L_3(C_1C_2C_3-C_1S_2S_3)+C_1C_2L_2 \\ 0 & S_2C_3+C_2S_3 & -S_2S_3+C_2C_3 & L_3(-S_2C_3+C_2S_3)+S_1L_2+L_1+b \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{array}
\qquad (1)
$$

FINDING SUITABLE LINK LENGTHS:

Calculating the suitable articulated arm lengths, we are using equation no. (1). Here our robot arm location is fixed so θ1 is zero. θ2 and θ3 are positional angles of the first arm.b is height of first arm joint L1,L2 and L3 are the lengths of arms. We have taken different lengths of arm and selected the most suitable length as per end position of the end effector. Table no.(1) gives us results of suitable arm length.

Sr No	INPUT							OUTPUT			Remark
	θ1	θ2	θ3	b (mm)	L1 (mm)	L2 (mm)	L3 (mm)	X	Y	Z	
1	0	120	60	100	250	250	250	0	134	152	
2	0	120	60	100	300	300	300	0	161	162	
3	0	120	60	100	400	400	400	0	215	183	OK Suitable Position
4	0	120	60	100	500	500	500	0	268	204	
5	0	120	60	100	600	600	600	0	322	224	

Table.1 Link Lengths Calculation and selection

ASSEMBLY PARTS DESIGN

Mechanical calculation:

End effector bracket: it is used for holding the tool. Tool holder design is similar to cantilever structure and all forces are coming vertically at distance shown in fig no.6.One side of the tool holder is fixed with the arm and another side is open for holding the tool. We have considered material with grade in mild steel as per availability and machining requirements. We are using hollow standard square pipes for developing articulated robot arms. We are calculating material thickness using dimensions and bending moments as per applying load.

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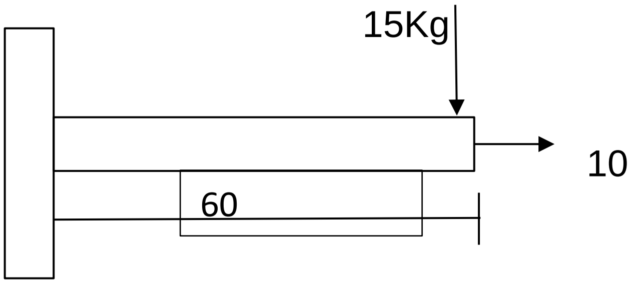

Fig.6 End effector mounting bracket design, now we find out required thickness using material as below

Material = ASTM A53 Grade B
Length of plate L = 60mm
Width of plate b = 28mm
Plate thickness d =?
Mass of End effector m = 12kg
Factor of safety = 2
Axial Load F_y = 147.15bN
Yield strength = 240MPa

2.3.1.1 Now find out allowable stress calculation

$$\sigma_{max} = \frac{Ys}{F.S} \quad (2)$$

$$\sigma_{max} = \frac{240}{2} = 120 \text{ MPa} = 120 \text{ X } 10^5 \text{ N/mm}^2$$

2.3.1.2 Cross sectional area of holding tool

$$A = B \times D \quad (3)$$

$$A = 60x28 = 1680 \text{ mm}^2$$

$$F_y = 147.15 \text{ N}$$

$$F_r = \sqrt{F_x^2 + F_y^2} \quad (4)$$

$$F_r = \sqrt{98.1^2 + 147.5^2} = 176.85\text{N}$$

2.3.1.3 Bending Moments after applying tool load

$$M = F_y \text{ X } L \quad (5)$$

$$= 147.15x60$$

$$= 8820 \text{ Nmm}$$

2.3.1.4 Maximum bending moment after applying tool load

$$M = \sigma_{max} \text{ x } Z \quad (6)$$

$$Z = 73.5 \text{ mm}^3$$

2.3.1.5 Plate section modulus

$$Z = \frac{bd^2}{6} \quad (7)$$

$$d^2 = \frac{Zx6}{b}$$

$$= \frac{73.5x6}{28} = 3.96$$

d = 4mm

2.3.2 Analysis of End effector mounting bracket

We are making the free body diagram as per fig no.7 and showing all moments and forces at the nodes

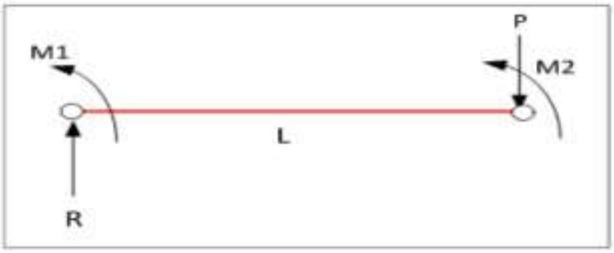

Fig.7 Free body diagram of End Effector

2.3.2.1 Now find out reactions at end,

$$R_1 = P = 147.15 \text{ N}$$

2.3.2.2 Now find out, Bending Moment at end,

$$M = -P(L-x) \quad (8)$$

$$M_1 = -147.15x(60-0) = -8.829 \text{ Nm}$$

$$M_2 = -147.15x(60-60) = 0 \text{ Nm}$$

2.3.2.4 Shear force

$$Vu = P = 147.15 \text{ N}$$

The mathematical equation [19] of forces vector using stiffness and displacement gives us below equation with considering applied loads and the displacement,

$$[F] = [K].[\boldsymbol{\delta}] \quad (9)$$

In the equation no 9 following terms are used,
[F] = the element of end forces vector
[K] = the element of stiffness matrix
[$\boldsymbol{\delta}$] = the element of displacement matrix
Theoretical results for End effector or tool holder are as follows,

1. Maximum bending moment M_1= -8.829 Nm (10)
2. Maximum shear force Vu = 147.15 N (11)
3. Deflection of beam at L = -0.013144 mm (12)
4. Slope of beam at L = -3.39 rad (13)

MODELING AND FEA ANALYSIS OF PARTS:

We used Solidworks 3D CAD software for CAD modelling fig no.8 and analysis. Solidworks 3D CAD Modeling gives output files in multiple formats like iges,.dxf,. sldprt. sldasm. Using Solidworks FEA analysis was carried out with providing details of material properties, force directions and mesh parameters. All components part Modeling and assembly done. Fig no.8. is the CAD model of articulated robot arm. It has a total 3 arms and end effector for tool holding.

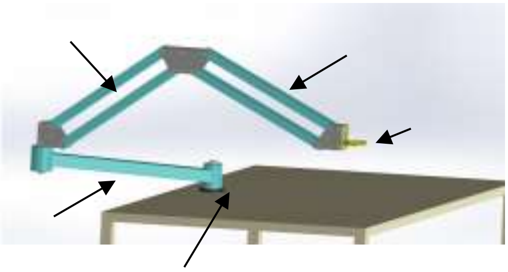

Fig.8 CAD model of articulated robot arm

After model build, we are performing analysis work on part. First, we have taken a tool holder for analysis. On the tool holder we are applying tool forces on the holding area. Fig no 9 is the analysis model, forces applied vertically on the tool holder. Fig no.10 is the displacement model after applying forces.

We are finding below results on analysis model

2.4.1 Von Mises Stress Analysis fig.9

1. Analysis maximum stress value = 1.02 X 10^8 N/m^2 (14)
2. Maximum portion of part is showing less stress area

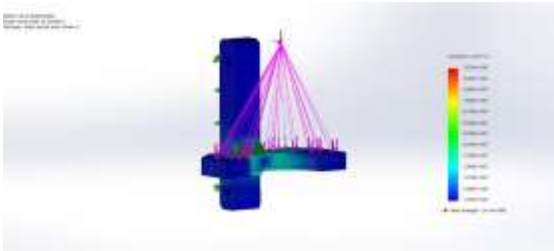

Fig.9 FEA Von Mises Stress Analysis of parts

2.4.2 Displacement Analysis fig.10

1. Analysis displacement value = 0.004672 mm (15)
2. Maximum portion of the part is showing less deformation.

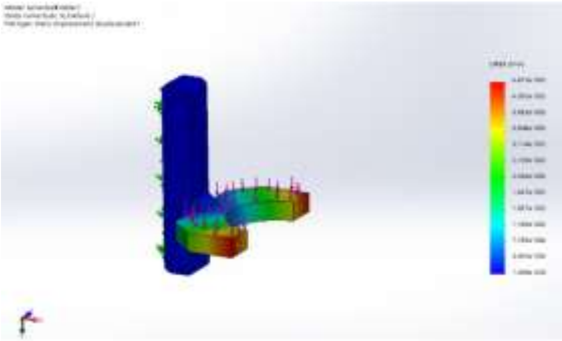

Fig.10 Displacement details of end effector

2.4.3 Strain Analysis fig.11

1. Analysis strain maximum value = 4.99×10^{-5} (16)

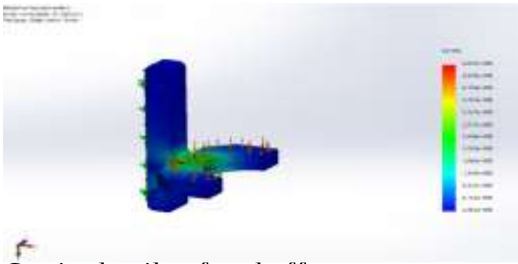

Fig.11 Strain details of end effector

EXPERIMENTAL MODEL:

Articulated robot arm built using design data, specified material and using fabrication and machining processes. Fig no.12 is the mechanical model of an articulated robotic arm. Screw driver is fitted as an end effector. Experimental analysis done on mechanical models.

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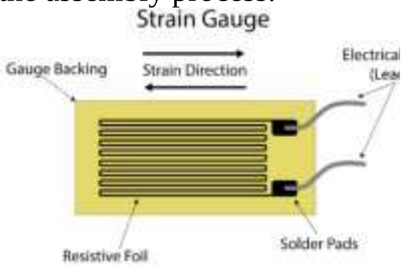
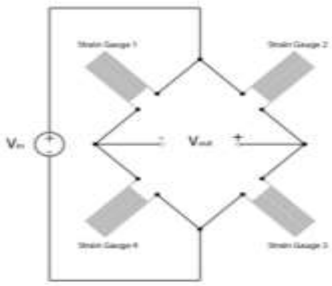
Fig .11 Developed model

EXPERIMENTAL ANALYSIS MEASUREMENT DETAILS:

We are using a strain gauge with location on the End effector arm, we found below readings during the assembly process.





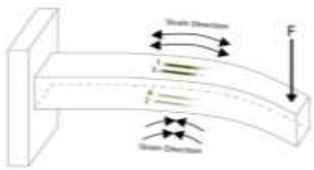


Fig .12 Strain gauge construction **Fig .13 Strain gauge circuit diagram**

We are applying voltage on gauge from 1 to 3VDC, a per arm movement and screw assembly working using an articulated arm we found below values were recorded at output of strain gauge circuit table no.12

Gauge Factor = 2

Sr No	Measured Values in Vout µV
1	1.800
2	1.950
3	1.980
4	2.120
5	2.230

Table No.2 Strain Gauge Readings

CALCULATING THE STRAIN:

We are using the following formula to convert the output values measured using strain gauge from voltage to strain [20]

$$\epsilon = \frac{V_{out}}{V_{in}} \text{ X } \frac{1}{G} \qquad (17)$$

where:

1. Vin is the input voltage (3V DC),
2. GF is the gauge factor of the strain gauge
3. Maximum Vout = 2.230µV

$$\text{Strain} = \frac{2.230 \text{ X } 10^{-6}}{3 \text{ X } 2}$$

$$= 0.366 \text{ micro strain}$$

$$\text{Strain} = 3.71 \text{ X } 10^{-7}$$

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RESULTS AND DISCUSSION:

Results

FEA Results:

Here we are comparing the FEA analysis results with theoretical value. We are comparing mechanical and functional parameters of articulated robot arms. Here we are finding whether the mechanical designed model is safe or not.

After comparing, we found the below results.

Sr No	Theoretical / Experimental Analysis Details	Result Value	FEA Details	Result Value	Remark
1.	Maximum Allowable stress	1.2×10^{8} N/mm	Von Mises Maximum stress	1.02×10^{8} N/mm	FEA analysis results are lower than theoretical result, hence design is Safe
2.	Maximum deflection	0.0131 mm	Maximum displacement	0.004672 mm	FEA analysis results are lower theoretical values, hence design is Safe
3.	Experimental Strain	3.71×10^{-7}	FEA strain	4.99×10^{-5}	Experimental strain results are lower compared with FEA results, hence design is Safe

Table No.3 Result Details of End Effector

Functional Results.

Articulated arm handling is fast and precise compared to traditional manual methods. Vertical angular position of tapping and screw is matching without holding additional alignment.

1. Reduction in cycle time almost 50% with earlier cycle time.
2. Arm suitable for multiple location screwing as per assembly layout.
3. Tool position angle varies from 0°,90° degrees suitable for horizontal and vertical assembly operations.

Discussion:

Mechanical design of Articulated Robot Arm gives required results. Cycle time using existing assembly methods is reduced. Theoretical calculation gives us ideas for parts selection, FEA results gives us results for design optimization. Experimental results give us clarity on mechanical functioning. Manufacturing of this type of articulated arm is easy so the required cost is low. Mostly this type of arms can be used for industries with further optimization in design and material with added features like controlled mechanism. This particular mechanical model changes the production process with an optimized model. This solution is used for low skill manpower as well as increasing productivity. This particular model reduces overall manufacturing cost in percentage and problem of skilled labour shortages.

CONCLUSION:

Articulated robot Arm is useful and end used satisfied with its performance. This design gives satisfactory results considering reduction of cycle time. This unit gives reduced operator fatigue of holding screwdriver with end torque. All torque and forces were taken care of by the articulated robot arm only. Easy handling of end effector or screw driver gives no slippages during assembly operation.

Arm suitable even though operator is unskilled to handle screw assembly process. This model can be used for assembly process where multiple screw assembly required and position of every screw is with any direction. This has only fixed angle movement position. This arm is mechanically functional for various operations including assembly, machining, resistance welding. Additionally, it requires servo motors and gear mechanism for movement of these arms. Servo motor and controller can be used for repetitive work applications. Design is optimised further optimisation possible with changing arm material properties. Also changing end effector design with feasibility to change angular position to any angle solves assembly of multiple products using any angle of tool position.

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