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Design and Analysis of Cost-Effective Cylindrical Robotic Arm

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Abstract: **Industrial production is nowadays driven by global competition and the need for fast adaptation of production to ever-changing market requests. These requirements can be met only by radical advances in current manufacturing technology. Most of the industries in the recent day are concentrating on CNC machineries for mass production of heavy components to improve productivity but loading and unloading of job is carried out manually. However, presently machine tool manufacturers are coming up with solutions including automatic loading and unloading to reduce the fatigue of labour and reduce cycle time, increasing productivity and hence efficiency. This project is discussed mainly on design and structural analysis of a cylindrical (RPP configuration) robotic arm for loading and unloading of the components, which in turn reduces the cycle time & also require less labour work. The CAD geometry of the project is prepared in Solidworks and validated by using FEA considering von-mises stresses and displacement theory to find the effects of payload on motors and critical components of the project. This project also focuses on the cost-effective measures that can be taken for the automation, as high cost is the only major issue to deal with.**

Keywords –Cylindrical Robotic Arm, CNC, Cycle time, FEA, RPP Configuration, Automation.

I. INTRODUCTION

Industry in this generation is increasingly going for automation mainly to live up to the need for increased productivity and delivery of final products ensuring uniform and standard quality. The rigidity as well as usually high cost of hard-automation systems, which were used to impart automation in the past, have eventually led to a keen interest in the use of electro-mechanical arm having potential of performing numerous manufacturing tasks in a flexible and handy environment at comparatively lower costs.

Industrial robot is referred as a re-programmable, multi-function manipulator aimed at displacing material, raw or finished parts, machine tools or specialized devices via variable programmed motions to carry out a variety of tasks. Robotic arms have a range of types such as- Cartesian robot, Cylindrical robot, Spherical robot, Articulated Parallel robot, SCARA robot, anthropomorphic robot (Human hand like Robot).

Loading and unloading of components on CNC or heavy machineries are repetitive and tiring tasks that require more labor work. Automation in such applications can noticeably increase productivity. Moreover, it will reduce human efforts required for such tasks enabling the labor force to work actively.

Our Project mainly emphasizes on developing a cost effective cylindrical robotic arm which will load and unload a component on a machine fixture with minimum labor effort. The proposed robot is an electro-mechanically operated machine that will handle different sized components of different properties.

II. PURPOSE AND METHODOLOGY

The main intension of designing a cylindrical robotic arm is to minimize manual operation of picking the component from stack to a significant extent and establish an semi-auto feeding mechanism which being a continuous structured process will elevate the productivity. This project also focuses on the cost-effective measures that can be taken for this automation process.

Electrical systems are faster than any other mechanical systems and have a good efficiency as well. But when a lot of power is needed, they must be coupled with other

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mechanical systems, which go on reducing the overall efficiency of the system. They however need lower maintenance than the other two. They do have great degree of control, as in case of steppers and servos. Pneumatic systems are fast but not as fast as the electric systems and at the same time not as slow as hydraulic systems. They can take higher loads than electrical systems, but they are not economical. Hydraulic systems can withstand very high loads, as well as a great degree of control, however they lack speed which is a must factor in robotics. Another major drawback is they require timely maintenance and refilling due to leakages, as well as storage reservoirs of oil. After comparing all the three systems, according to the requirements of our application, it is convenient to use electromechanical system.

We have analyzed conventional system by considering applications and operational conditions. Considering the space constraints, the dimensions, sizing of robotic arm and actuating mechanisms are finalized. For the validation of design safety, we have considered the Factor of Safety concept. Furthermore, calculations of dynamic load carrying capacity and structural analysis clearly validates the lateral robotic arm design.

III. LITERATURE REVIEW

SEGLA Stefan [1] has published a paper on. “Static Balancing of Robot Mechanisms and Manipulation Devices” which helped in understanding static balancing of cylindrical robotic mechanisms and manipulation devices by using spring balancing mechanisms.

Harish K, Megha D, Shuklambari M, Amit K, Chaitanya K Jambotkar [2] have worked on “Pick and Place Robotic Arm Using Arduino”. In this article, the pick and place robot similar to the arm discussed in this paper had been implemented to ease the process of sorting, moving materials etc. We extracted valuable data regarding reduction of human interference and errors to achieve desired precise output.

T. Uenoa, N. Sunagaa, K. Brownb and H. Asada [7] have published a paper on “Mechanism and Control of a Dynamic Lifting Robot”. Which was mainly based on the design and control of robot for high load application. This helped us to identify factors to be considered for robotic arm with ability to handle heavy loads.

Gurudu Rishank Reddy, Venkata Krishna Prashanth Eranki [9] have submitted a thesis on “Design and Structural Analysis of a Robotic Arm”. The thesis so presented informed about actuation of a typical robotic arm which helped us in deciding parameters of proposed cylindrical arm for optimum performance along with due considerations of structural analysis.

Krishnaraju A, Ramkumar R, Lenin V R [11] published their work on “Design of Three Fingered Robot-Gripper Mechanism”. Study of this paper enabled us to overcome the challenges faced while designing the three fingered gripper mechanism used for picking and dropping action. Thesis presented in this paper valuably assisted us for force calculations of the gripper.

IV. DESIGN AND CONSIDERATIONS

4.1. Technical parameters

4.1.1. Industrial Application and Requirements

Application- Loading and Unloading of the component into a fixture

Requirements-

- Heavy load lifting capacity with rigid structure
- Simplicity in model for handling, manipulating and controlling Easy position control
- Moderate flexibility
- Low maintenance, initial and operational costs

4.1.2. Selection of Robot Configuration

Based on the above requirements and application, optimum configuration selected for robotic arm is Cylindrical (RPP) robotic configuration as in Fig. 1. It is also called as a cylindrical co-ordinate robot as work area of the robot is cylindrical.

Features of RPP configuration -

- One revolute joint for swinging the arm back and forth about vertical base axis
- Two prismatic joints, one for the wrist to move or end effector along vertical axis and other is for radial action to and fro translation.
- Work envelope is in cylindrical shape.

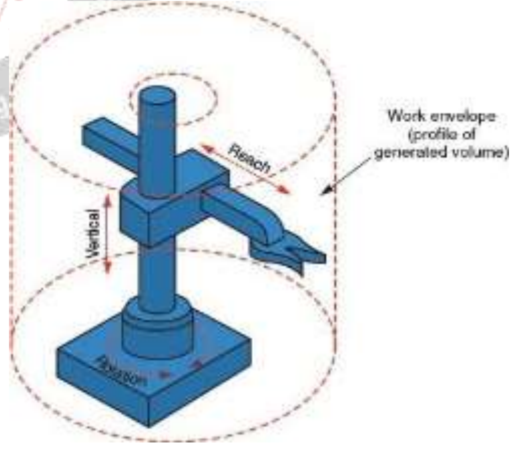

Fig. 1: Cylindrical robot configuration

4.1.3. Selection of actuating mechanism and path of travel

Based on the requirement of the facility and availability of resources, electromechanical approach is optimum for the system. There are numerous types of motors that are currently used in automation industry such as Permanent magnet, brushless DC, Servo and stepper motors, Induction motors and Geared DC motors. Among these options,

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Geared DC motors are selected and used to impart various motions as these are most suitable for the linear actuating mechanism.

Geared DC motors are an upgraded version of Brushless DC motors that are relatively less noisy in operation, provide higher torque, higher speeds and are not fragile.

Five desired motions that are employed, are all based on DC actuation.

- Two motors for vertical and horizontal travel of the arm.
- Two motors for Gripping mechanism, one to grip the component and One to rotate the gripped component.
- One motor for revolution of the robotic arm through lead screw.

4.1.4. Selection of materials

Materials to be selected must possess the necessary physical, mechanical, chemical properties for the proposed application.

The parameters based on which the materials are selected are as follows:

- Weight
- Surface finish
- Rigidity
- Tensile, Compressive and shear strength
- Bending, Torsion, Buckling load
- Hardness

Selection of materials is also concerned with some other important parameters such as material cost, the quality of the material to be imparted, availability of materials at desired demand and time, economic alternative material considerations in case of shortage and space considerations for system. Material details and specifications are mentioned in table no. 2 with an idea of the proposed model in figure 2.

1.	Robot configuration	Cylindrical
2.	Degrees of Freedom	4
3.	Number of axes	4
4.	Maximum Payload	313gm
5.	Work envelope	Volume= $6.3125*10^7$ mm^3 Surface area= $1.1035*10^6$ mm^2
6.	End effector	Mechanical- Gear gripper
7.	Mass of robot	8 kg
8.	Drive	Electro-mechanical
9.	Actuator	DC geared motors
10.	Controller	Switch operated
11.	Repeatability	Less than 5mm

Table 1: Design specifications

4.1.5. Design

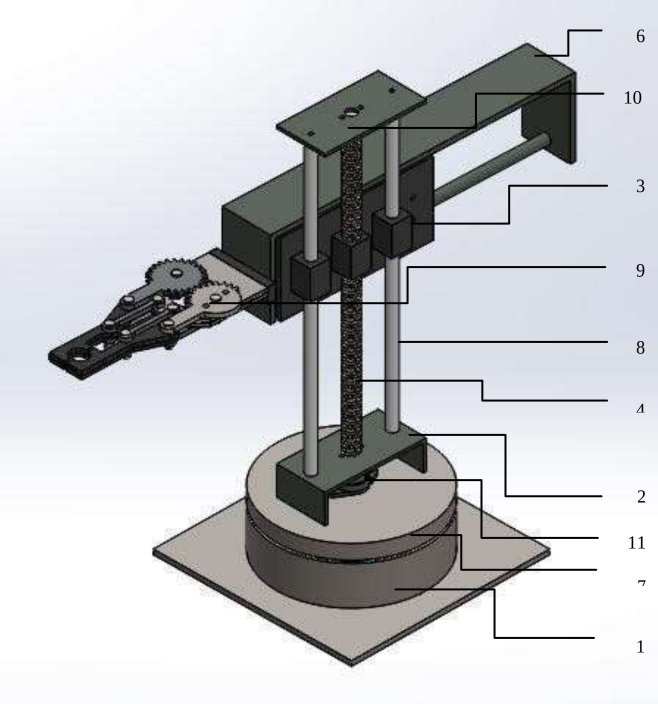

Fig. 2: Robotic arm assembly view

Sr. no	Description	Purpose	Material Selected
1.	Base	Foundation to whole assembly	Cast Iron
2	Base Plate	To support lead screw & steel rods	Mild Steel
3.	Lift	To provide vertical travel to arm	Cast Iron
4.	Lead Screw	Actuating mechanism for vertical travel	Alloy steel
5.	Rack and Pinion	Actuating mechanism for horizontal travel	Hardened Steel
6.	Slider	To translate gripper along radial axis	Mild Steel
7.	Rotary Disc	To provide rotary motion to arm	Medium Carbon Steel
8.	Supporting Rods	Rigid support to lead screw & lift	Stainless steel
9.	Two finger gripper	Pick and Place handling application	Anodized aluminium
10.	Top plate	To provide housing for motor	Mild steel
11.	Pillow block bearing	To enable rotational movement & support to lead screw	Cast iron

Table 2: Components list

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V. CALCULATIONS

5.1. Payload calculations

Maximum payload will be depending upon the following factors:

- Moment of inertia of beam cross-section i.e. Shape, Size and Dimensions of beam Length of beam
- Maximum allowable deflection Force acting due to mass of beam
- Force acting due to mass of component Force acting due to mass of gripper

To avoid failure due to overloading, we are assuming the slider as a cantilever beam as in Fig. 3 with rectangular cross-section as in Fig. 4. For a cantilever beam, maximum deflection will be at its free end with point load.

Therefore, Considering a cantilever beam with point load at its free end,

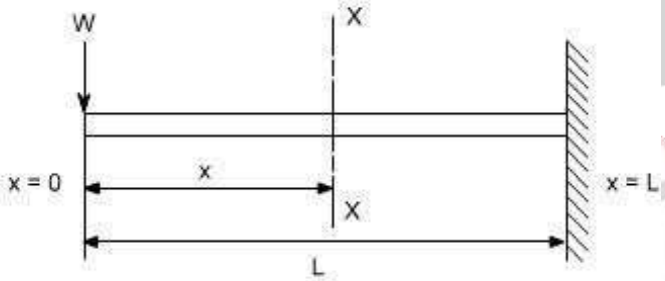

Fig. 3: Cantilever beam with point load at free end 50

W= 9.6446 N

Maximum bending moment

M= W*L = 9.6446* 300*10^{-3} = 2.893 N-m

For beam,
Mass of beam = Volume x Density
= 75 x10^3x10^{-9}x 7850
= 0.58875 kg

Force acting due to mass of beam= 0.58875x9.81
= 5.7756 N

For gripper,
Gripper volume=
10371.81 mm^3 Mass
of gripper= Volume x
Density
= 10371.81x10-9x 7850 x9.81
= 0.7987 N
To determine maximum payload,
[Total Force acting on the free end] – [Force acting due to mass of beam] = [Force acting by mass of gripper] + [Force acting due to mass of component]
[9.6446] – [5.7756] = [0.7987] + [m x 9.81]
[m x 9.81] = 3.0703 N

Maximum payload
m= 3.0754/ 9.81 = 0.31297 kg
or
m= 312.97
gm i.e.
approx. m=
313 gm.

M = -W*x

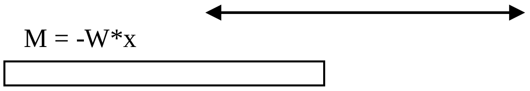

Fig. 4: Cross-section of beam

5.2. Force calculations of the gripper

To simulate multiple gripping actions, we have emphasized on 3 main apertures of the gripper namely medium, minimum and maximum represented by Figures

Maximum allowable deflection for cantilever, Ymax = Span/360 mm

Maximum deflection for cantilever beam with point load at free end is given by,

Ymax = WL^3/3EI

I = bd^3/12 = (50*5^3)/12 = 520.833
mm^4 E = 200*10^3 Mpa
L = 300 mm

Ymax= 300/360 = 0.8333

W= (Ymax*3EI)/L^3
= (0.8333x3x200x10^3)/300^3
= 9.6446 N
5,6 & 7 respectively.

Gripping Force (Fg) Calculations:

Motor used for the gripping action is selected on the basis of torque exerted by the motor.
For optimum use of the gripper, a motor of 150 RPM with torque specification of 0.8 kg-cm is selected.
T = F · r F= T/r
F=

78.48/21

= 3.7371

N F =

3.7371

N

Minimum aperture:
$\alpha=68.02$
$\beta=0$
$\phi=90$

$F_1 = F \cdot \cos(\alpha) = 3.7371 x \cos 68.02$ $F_1 = 1.3987$ N $\Sigma Fx = 0$

$- F_1 \cdot \cos(\alpha+\beta) - F_2 \cdot \cos(\varphi) + Fgripper = 0$

$Fgripper = 1.3987 \cos(68.02) + F_2 \cdot \cos(90) = 0.5235$ N

Fgripper= 0.5235 N
$\Sigma Fy = 0$
$F_1 \cdot \sin(\alpha+\beta) - F2 \sin(\varphi) = 0$
$F_2 = F_1 \cdot \sin(\alpha+\beta) / \sin(\varphi) =$

1.2970 N $F_2 = 1.2970$ N

Medium aperture:
$\alpha=19.29$ $\beta=48.67$
$\phi=41.38$

$F_1 = F \cdot \cos(\alpha) =$

3.5271 N $\Sigma Fx = 0$

$- F_1 \cdot \cos(\alpha+\beta) - F_2 \cdot \cos(\varphi) + Fgripper = 0$ Fgripper = 1.3235 $+ F_2 \cdot \cos(41.38)$
$\Sigma Fy = 0$
$F_1 \cdot \sin(\alpha+\beta) - F_2 \sin(\varphi) = 0$
$F_2 = F_1 \cdot \cos(\alpha+\beta) / \sin(\varphi) = 4.9456$ N
$F_2 = 4.9456$ N
Fgripper=

5.0344 N

Maximum

Aperture:

$\beta = 68.96$
$\phi = 21.32$

$\Sigma Fx = 0$
$- F_1 \cdot \cos(\beta) - F_2 \cdot \cos(\varphi) + Fgripper = 0$
Fgripper= 3.7371cos (68.96) + 9.5934(cos 21.32) Fgripper = 10.278 N

$F_2 = F_1 \sin(\beta) / \sin(\varphi) =$

9.5934 N $F_2 = 9.5934$ N

Maximum gripping force (Fgripper) must be greater than the force exerted by the weight of the component to avoid the slip of the component from gripper jaws/fingers.

As, Fgripper= 10.278 N is greater than Force exerted by the weight of the component i.e. 3.0754 N, the gripper is optimum for this application.

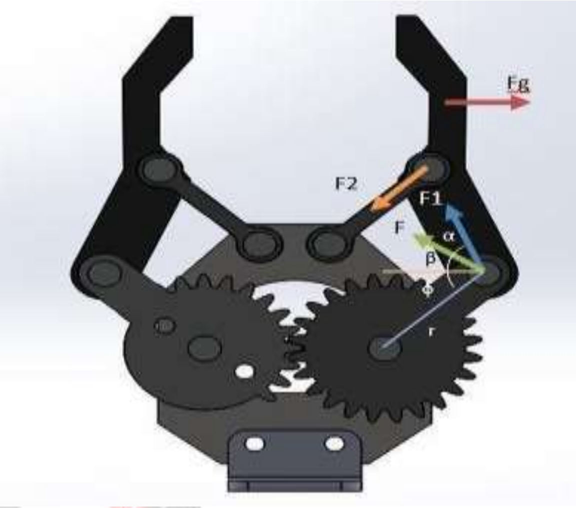

Fig. 5: Medium aperture

Fig. 6: Minimum aperture

Fig. 7: Maximum aperture

5.3. Work envelope calculations

The work envelope is simply work volume which can be reached by an arbitrary point located at the end of the robotic arm.

Basically, it's a solid geometry created when the manipulator reaches maximum and minimum of forward-backward or Up-down reach. These distances depend on

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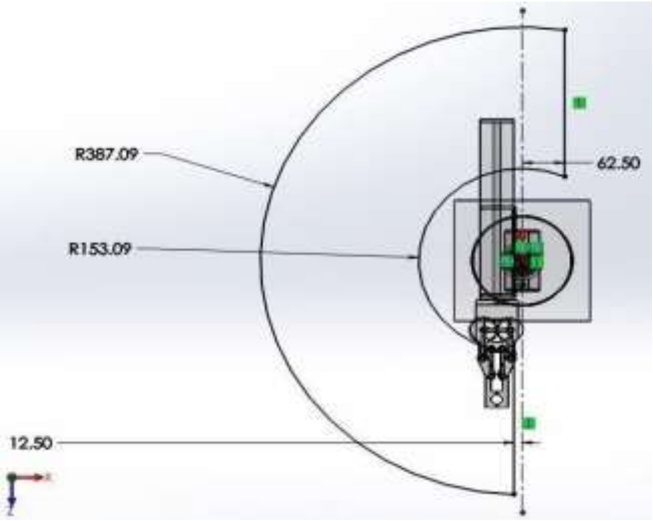

Fig. 8: Work envelope top view for the prototype

length of a robot's arm and the structure of its axes.

Dead zones are referred to as the areas within the work envelope that remain untouched by the robotic arm.

The work envelope of this configuration naturally takes a cylindrical shape as shown in Fig. 8. Since there is a restriction on the movement of the retraction of the arm due to confined geometry, a cylindrical dead zone around the robot structure. Fig. 9 shows a fabricated prototype.

Please note following dimensions are calculated for prototype meanwhile the scale factor is 4.

Work envelope radius when the slider is at its retracted position = 153.09 mm

Work envelope radius when the slider is at its extended position = 387.09 mm

Volume=

$6.3125*10^7$ mm^3

Suface area=

$1.1035*10^6$ mm^2

VI. EXPERIMENTAL VALIDATION AND ANALYSIS

6.1. FEA validation results using Ansys 16.0

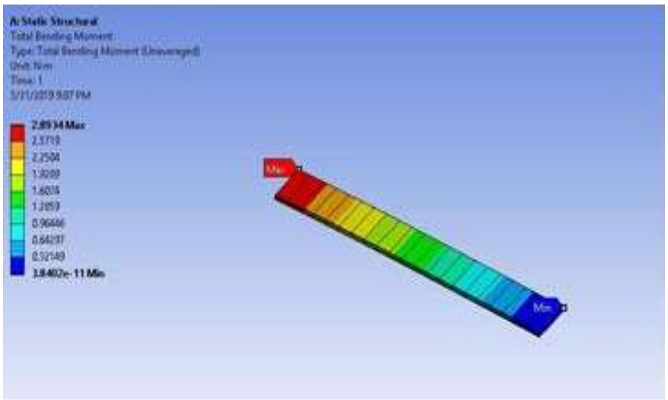

Fig. 10: Total ending moment

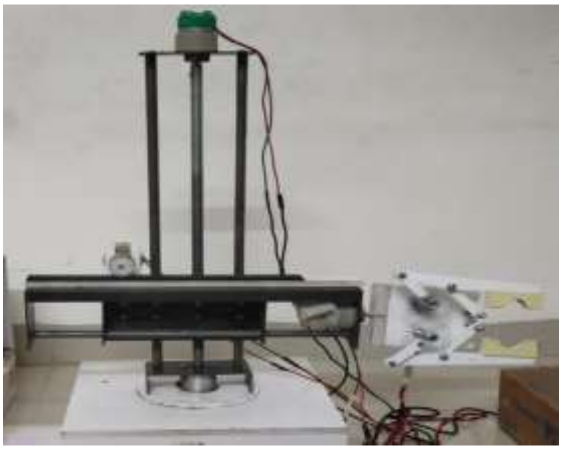

Fig. 9: Fabricated Prototype

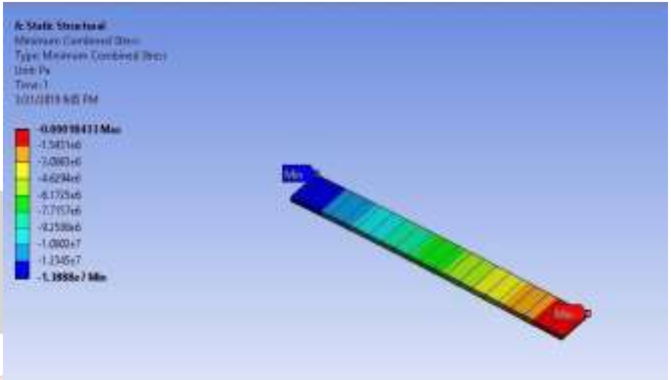

Fig. 11: Minimum combined stress

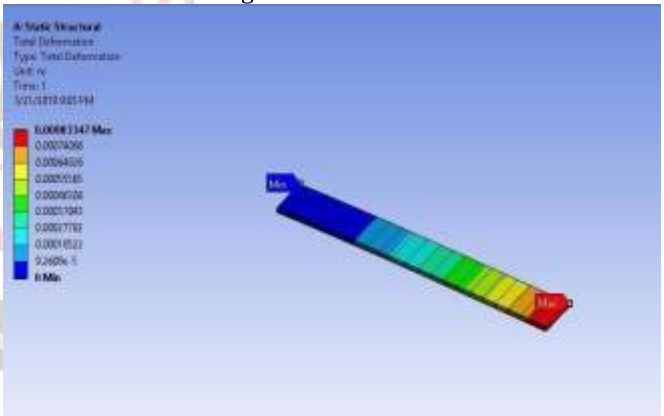

Fig. 12: Total Deformation

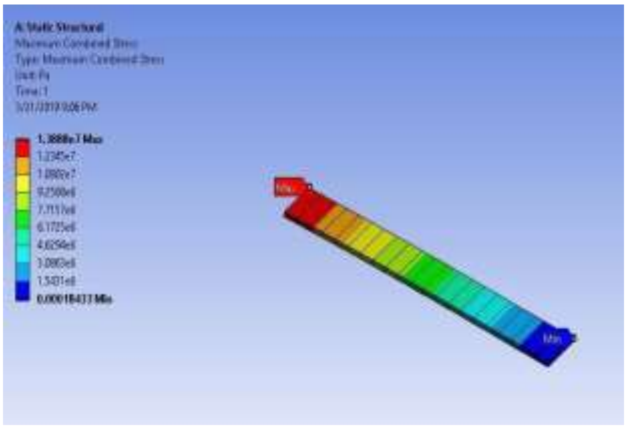

Fig. 13: Maximum combined stress

Finite element analysis has been successfully carried out using Ansys 16.0 on translating robotic arm having

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vertical and horizontal travel. As maximum load is to be applied on extreme end of the arm when it is at its maximum reach, it acts like a cantilever beam. Considering deflection limits, maximum allowable deflection is 0.833 mm for which 300 mm length arm can sustain 10N maximum load. Hence design is safe considering factor of safety as 1.1.

The following results are obtained from this analysis:
1. Total Deformation = 0.8330 mm
2. Total Bending Moment = 2.892N-m
3. Minimum Combined Stress = -1.8433 MPA
4. Maximum Combined Stress = 13.8 MPA

6.2. Testing and Repeatability

Standard Deviation:

An industrial robot has numerous metrological _______ parameters, which essentially have a direct impact on the effectiveness of the robot while it is being operated. Two most prominent such parameters are repeatability and accuracy. In general terms, repeatability of robot can be defined as its ability to repeat ongoing task precisely in the

$li_1 = \sqrt{}\,(3.9 - 3.7)^2 + (23.5 - 23.53)^2 + 0 = 0.2022$

$li_2 = \sqrt{}\,(3.7 - 3.7)^2 + (23.5 - 23.53)^2 + 0 = 0.03$

exact manner. Whereas accuracy is the difference between the desired output and the obtained output.

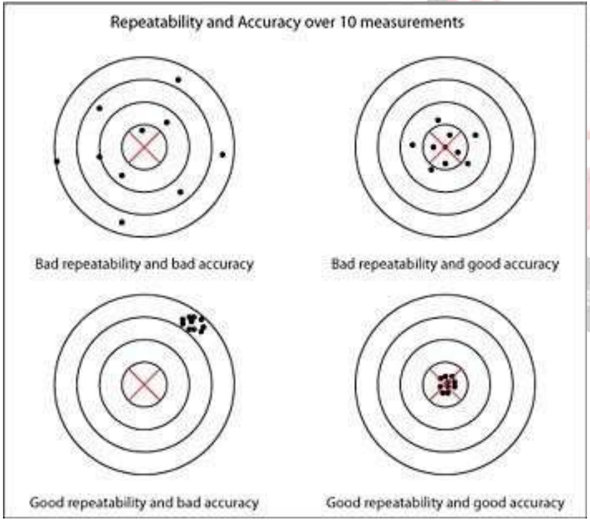

Fig. 14: Repeatability & Accuracy concept

The absolute position accuracy is the ability of the robot to target a specific position with least possible error. To ensure optimum working of the robotic arm, it is necessary that these factors are carefully considered.

For robotic applications, repeatability and accuracy has been measured at pessimistic values, using maximum speed of operation and maximum payload.

For N measurements, with commanded position (X_c, Y_c, Z_c) and reached position (X_r, Y_r, Z_r):

Average:

$\bar{X} = 1/3\ (X_{r1} + X_{r2} + X_{r3})$

$\bar{X} = 1/3\ (3.9 + 3.7 + 3.5)$

$\bar{X} = 3.7$

$\bar{Y} = 1/3(Y_{r1} + Y_{r2} + Y_{r3})$

$\bar{Y} = 1/3(23.5 + 23.5 + 23.6)$

$\bar{Y} = 23.53$

As, Z coordinate is kept constant for all the three readings, average will be the original value.

$\bar{Z} = 32.2$

$li_3 = \sqrt{}\,(3.5 - 3.7)^2 + (23.6 - 23.53)^2 + 0 = 0.2118$

$\bar{l} = 1/3\ (li_1 + li_2 + li_3)$

$\bar{l} = 0.1480$

$S_l = 0.1023$

$li = \sqrt{(X_r - \bar{X})^2 + (Y_r - \bar{Y})^2 + (Z_r - \bar{Z})^2}$

$RP_l = \bar{l} + 3S_l$

$RP_l = 0.1480 + 3*0.1023$

$RP_l = 0.4549$ cm i.e. 4.549 mm.

Above calculations show that the repeatability of the robotic arm is less than 5 mm.

According to statistics theory, using this formula, it means that the position of the robot will be 99.8% of the time inside the repeatability range.

6.3. Time measurement

Sr. No.	Time taken for 90-degree rotation of the arm (s)	Time taken for loading / unloading of component (s)
1	1.2	65.3
2	1.4	67.1
3	1.8	64.2
4	1.4	66.7
5	1.4	65.7
6	1.5	67.1
7	1.3	66.3
8	1.3	65.9
9	1.6	64.8
10	1.7	65.5
Avg. Time	1.46	65.9

Table 3: Time measurement

6.4. Payback period calculation

While planning to purchase the capital equipment, prior calculation of the Payback period was a

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determining factor for this project to foresee the overall profitability of total initial investment. This is an important factor of the project aimed at determining the investment required, measure the impact of the investment on operations, cost etc.

Total proposed Robot system price	320000
Number of robots in proposed system	10
Number of workers per shift	10
Number of shifts per day	2
Total Number of operators	20
Annual employee wages	180000
Total labor cost	3600000
Number of robot operators per shift	3
Number of shifts per day for robot operators	2
Total Robot operators	6
Annual robot operator wages	180000
Total robot operator wages	1080000
Estimated return on investment (w/o considering maintenance)	9 months
Break Even Point (in value)	391538
Net Cost Savings	1st Year Return= 71970 5th Year Return= 1957760

Table 4: Payback period with maintenance calculation

Payback time is (P) is the cost of the robot divided by the labor cost minus the maintenance.

$$P = I / (L - E)$$

I = Total Capital Investment.
L = Cost of labor replaced by robot.
E = Cost of maintenance.

$$P = (320000 * 10) + (6 * 15000 * 12) / (20 * 15000 * 12) - (100000)$$

$$P = 1.2228\ years \text{ i.e. } 15\ months.$$

VII. COST-EFFECTIVE MEASURES

Depending upon the requirement of material properties for the robotic arm components such as Strength, Toughness, High load bearing capacity etc., suitable materials for various components are selected that serve the purpose at low cost.

By restricting the application of the robotic to a particular system layout, costs of extra automation and maintenance are effectively reduced.

Based on industrial application, we have selected the optimum configuration i.e. Cylindrical Configuration. This type of configuration has an additional degree of freedom than Cartesian configuration. Also, moderate flexibility is offered by this configuration, which is greater than Cartesian configuration but is less than SCARA type. Cylindrical configuration has a rigid structure and build of the robotic arm is such that it is capable of lifting heavy loads conveniently which is difficult to achieve by SCARA type configuration.

All the actuating mechanisms used are simple, purely mechanical and are less complex to manufacture.

Lead screw has provided a versatile and economical linear translational solution. Use of lead screws have enabled relatively smoother performance and have offered the flexibility needed for this particular application. Following are the advantages of lead screws over ball screws:

1. Low cost
2. Quiet in operation
3. Low vibration
4. Economical- 75% less cost than ball screw

However, it is less efficient than ball screw and backlash error may occur.

We have used anti-backlash nut in order to avoid backlash error. Anti- backlash lead screw nuts come in a selection of shapes and sizes. Anti-backlash nut solution utilizes an inbuilt compressions spring to ensure that the teeth of a lead screw mechanism remain consistently engaged and preloaded. This method of compensating for backlash is reactive and can remain effective even if the level of backlash is altered over time.

VIII. CONCLUSION

After analyzing numerous research papers, thesis and books on different types of robot configurations, like Cartesian, SCARA, Polar, etc., we came up with a Cylindrical configuration for the robotic arm that will reduce the human efforts involved in overall process of loading and unloading of a component on a machine fixture. Though it can be implemented in various methods, this method of implementation is the most feasible and cost effective. Design has been successfully implemented after simulating pick and place mechanism. Components and their material specifications are selected as per the industry application requirements and validated using FEA study for failure criterion. Carrying out proper calculations, analytical and FEA solutions for deformation, bending moment and stress were found to be nearly equal namely 0.83347 mm, 2.8934 N-m, Minimum Combined Stress: -1.8433 MPA & Maximum combined Stress: 13.8 MPA. The work envelope has been designed such that maximum area of plant is utilized and high precision & accuracy are obtained. The working volume for the proposed model is $6.3125*10^{7}$ mm3. Calibrating the machine many times, it was found that the average time taken by the machine to load or unload a component was nearly 66 seconds. With all the due considerations regarding payback period and maintenance costs, the capital amount invested in the proposed project will be recovered fully within a span of

1.5 years.

IX. REFERENCES

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