A Desktop SCARA Robot using Stepper Motors

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Abstract – *The paper describes the development and testing of 3 degree of freedom (DOF) desktop SCARA that is capable of picking and placing objects with high speed and precision. Using Autodesk inventor, the initial modelling of SCARA robot is created. The rotational inertias of the two links are calculated from the software and using parallel axis theorem. Using the considered values of peak speed and acceleration, torques of stepper motors are calculated. The inverse kinematics calculations are carried out in MATLAB software since the processing power of microcontroller is limited. MATLAB is so programmed to convert the angles into number of steps and sent to the microcontroller by serial communication. To enable the robotic arm to operate at high speed the inter-step delays for stepper motors are calculated using Taylor's series to provide constant acceleration and deceleration. A graphical user interface is designed using MATLAB. Finally, the electronic circuitry and mechanical parts are assembled, and the robot is tested for repeatability.*

***Key Words*: SCARA, 3-DOF manipulator, Pick-n-place, MATLAB, Inverse kinematics, Stepper motor.**

1. INTRODUCTION

The use of robots in industries is proliferating due to the necessity of automation, reducing worker fatigue and faster productivity. Robots applications in industries is primarily in four fields viz. material handling, operations, assembly and inspection. Apart from industries, robots are also deployed in home sector, health care, service sector, agriculture and farms, research and exploration. The applications of robots are only limited by the need and imagination of the developer and the end user. Robots have a potential to change our economy, health, living style, and the world we live in [1].

The SCARA acronym stands for Selective Compliance Articulated Robot Arm. It is selective compliant since the arm is fully compliant in the horizontal plane while it is rigid in the vertical axis. Also, the two-link arm layout imitates the human arm thus making it articulated. One joint acts as a shoulder joint and the second as an elbow joint [2]. SCARA robots are the first choice of industries due to high speed and accuracy. These robots are used generally for assembly, pick and place, sorting, soldering and painting. This work presents the design and fabrication of desktop robotic arm that can do its programmed movements with speed, accuracy and precision.

The focus is to bring robots for day to day applications for household and educational use. This SCARA robot is ideal for applications involving the manipulator to travel fixed coordinates. The robotic arm can be operated in manual as well as auto mode. The user can enter the sequence of operations into the HMI along with the desired speed and dwell time. The MATLAB program calculates the angles and instructs the stepper motor to attain the required coordinates. The vacuum pump and vacuum cup enable the robot to be used for pick and place operations. It is necessary to do referencing of the robot every time it is started [3]. The focus is to attain accuracy at high speed keeping the cost as low as possible. The methodology followed for development of the proposed SCARA robot is shown in fig – 1.

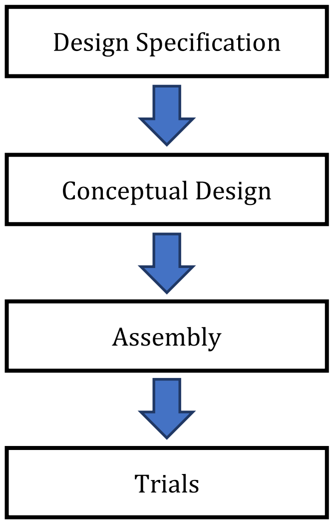

Fig – 1: Methodology

2. REQUIRED SPECIFICATIONS

In order to meet the requirements, SCARA robot is expected to have specifications as mentioned in table 1. Considering the application and the workspace, a robotic arm with R-R-P (Revolute, Revolute, Prismatic) configuration is selected. Fig – 2 shows the schematic diagram of the robotic arm. The end effector consists of a vacuum cup which will enable to pick and place objects.

Table -1: Required Specifications

Required specifications	
Specification	**Value**
Degrees of Freedom	3
Maximum payload	100 g
Maximum reach	300 mm
Peak planar speed	200 deg/sec
Peak vertical speed	50 mm/sec
Repeatability	0.05 mm

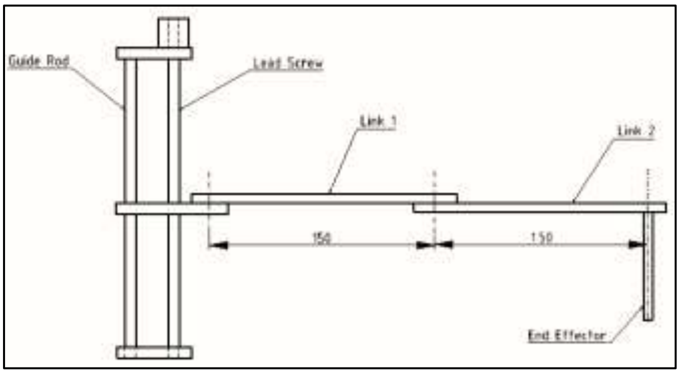

Fig -2: Schematic diagram of Robotic arm.

3. DESIGN

The proposed design of SCARA robot developed using Autodesk Inventor is shown in fig - 3 and the implemented design is shown in fig - 4. The robot comprises of two links in a parallel axis joint layout which are capable of movement in horizontal plane and a lead screw nut arrangement for movement in the z-axis. To ensure smooth movement in the vertical axis, four linear bearings are used along with guide rods to support the platform that supports the stepper motors. Aluminium extrusion beam is used as a substructure for rigid support of vertical axis stepper motor. Each of the links, as well as the lead screw, is driven by a separate stepper motor. The shaft of the second link is connected to the stepper 2 using belt and pulley arrangement to reduce the load on the arm. This enables selecting a motor with lower torque which eventually reduces cost. A 40 teeth pulley is used at output and 20 teeth at the motor shaft. This gives a speed ratio of 0.5 for link 2. The end effector is introduced in such a way that it allows various user requirements [4]. The materials are selected such that the rotational moment and the weight of the assembly are minimized. Motor supports and links are manufactured from acrylic material by laser cutting which also helps to reduce cost [5].

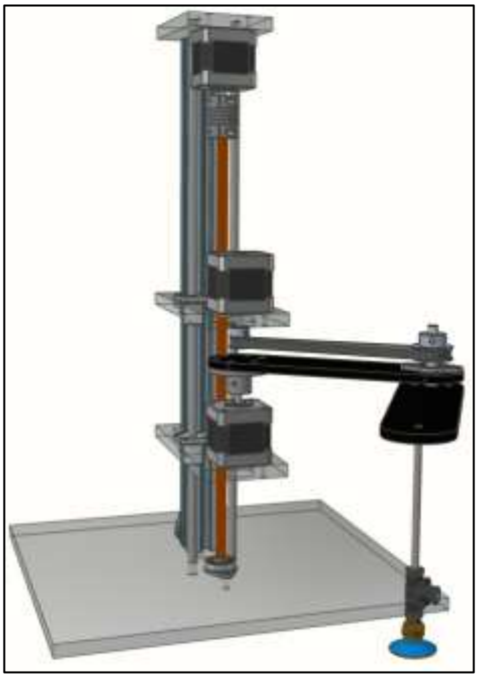

Fig - 3: 3D Model of Robotic arm.

Fig - 4: Actual model of Robotic arm.

The workspace of the SCARA arm forms a cardioid shape with outer diameter 600mm & inner diameter 100mm. Angular reach is 240 º. When the link 1 reaches ±120º the link 2 can be further extended to 120º.

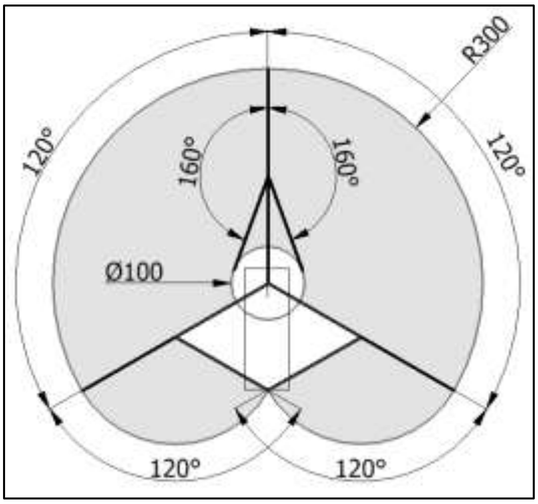

Fig – 5: Working Envelope.

4. INVERSE KINEMATICS

The inverse kinematics determine the angles θ_1 and θ_2 of joint 1 and 2 respectively to bring the end effector to the desired position (P_X,P_Y) [6]. Cartesian coordinates of the desired end effector position are entered in MATLAB which calculate the angles and convert to number of steps.

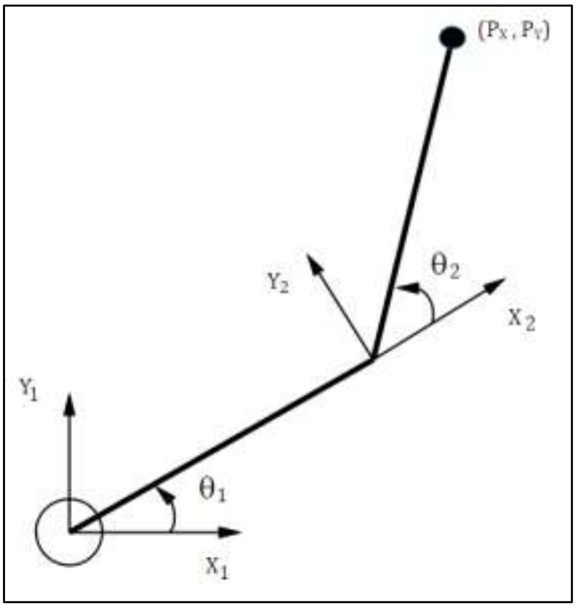

Fig – 6: Inverse Kinematics diagram.

If the Cartesian coordinates of desired end-effector location are given by (P_X,P_Y) and l_1 and l_2 are link lengths which are 150 mm each, the shoulder angle $\theta_1$and elbow angle θ_2 is given by equation (1) and (2).

$$\theta_2 = \cos^{-1}\left(\frac{P_X^2 + P_Y^2 - l_1^2 - l_2^2}{2l_1 l_2}\right) \quad (1)$$

$$\theta_1 = atan2(P_Y, P_X) - \cos^{-1}\left(\frac{P_X^2 + P_Y^2 + l_1^2 - l_2^2}{2l_1\sqrt{P_X^2 + P_Y^2}}\right) \quad (2)$$

The function $atan2(P_Y, P_X)$ can be defined as:

$$atan2(P_Y, P_X) = \begin{cases} \tan^{-1}\frac{P_Y}{P_X} & P_X > 0 \\ \tan^{-1}\frac{P_Y}{P_X} + \pi & P_X < 0, P_Y \geq 0 \\ \tan^{-1}\frac{P_Y}{P_X} - \pi & P_X < 0, P_Y < 0 \\ \frac{\pi}{2} & P_X = 0, P_Y > 0 \\ \frac{-\pi}{2} & P_X = 0, P_Y < 0 \\ undefined & P_X = 0, P_Y = 0 \end{cases}$$

Consider an end effector position P(184,206)

Since both the links are 150 mm each,

$l_1 = l_2 = 150$

Substituting the values in above equation,

$$\theta_2 = \cos^{-1}\left(\frac{184^2 + 206^2 - 150^2 - 150^2}{2\times150\times150}\right)$$

$\theta_2 = 0.801$ rad $= 45.943$ deg

$$\theta_1 = atan2(206{,}184) - \cos^{-1}\left(\frac{184^2 + 206^2 + 150^2 - 150^2}{2\times150\sqrt{150^2 + 150^2}}\right)$$

$\theta_1 = 0.441$ rad $= 25.257$ deg

The calculations are verified using Inventor software.

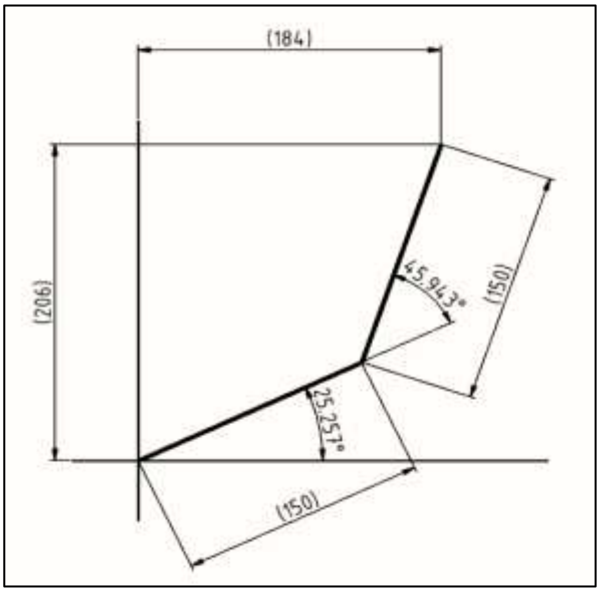

Fig - 7: Verification of inverse kinematics.

5. MOTOR SELECTION

Due to high accuracy and repeatability, stepper motors are selected for the application. To ensure proper working, steppers having torque greater than the joint torque of each joint are to be selected. The lagrange-euler formulation is used to calculate the joint torque [7]. The z-axis motor is selected on the basis to the torque required to overcome gravity and torque to overcome inertia.

Rotational Inertia at Joint 1= 20.88×10^{-3} Nm^2

Rotational Inertia at Joint 2= 4.36×10^{-3} Nm^2

The peak angular velocity is considered to be 200 deg/sec. and this angular velocity is achieved in 0.33sec

For Joint 1,

α= 10.577 rad/sec^2

τ=0.22Nm

=2.2kg cm

For Joint 2,

α= 10.577 rad/sec^2

τ=0.093Nm

=0.93 kg-cm

Hence, motor selected for Joint 1 is NEMA17-4.2kg cm & for joint 2 is NEMA17-1.4kg cm.

Peak lead screw nut speed is considered to be 50mm/sec.

A lead screw with four start and 2mm pitch is selected to minimize the stepper revolution.

Peak lead screw speed = $\frac{0.050\times 60}{0.008}$ = 39.26rad/sec

Assume lead screw efficiency =86%

Polar moment of inertia of lead screw (J_S) =38.8 x 10^7kgm^2

J_L= 1.134x10-6 kg m^2

J_S+J_L=5.01 x10-6

For vertical axis

Acceleration is considered to be 0.15m/sec^2

α =117.92rad/sec2

Torque to overcome gravity = $\frac{\sin\theta\times mg\times L}{2\pi\times\eta}$

= 0.1N-m

$T_j = 5.01\times10^{-6}\times 0.15$

$= 7.515\times10^{-7}$

$\tau_a = 7.515\times10^{-7} + 0.1$ = 0.1N-m = 1kg cm

Hence a stepper motor of 1.4 kg-cm is selected for vertical axis movement.

6. NUMBER OF STEPS PER DEGREE

Since the input to stepper motors is given as number of steps instead of angle, it is necessary to convert angle into number of steps. As the configuration of all the three steppers is different from each other, number of steps per degree is also different. Stepper 1 is directly coupled to link 1, Stepper 2 is connected to link 2 via belt pulley arrangement with reduction ratio of 0.5, while the stepper 3 is connected to the lead screw having 4 starts directly using a flexible coupling. The stepper motor driver DRV8825 supports six micro stepping modes viz. M0, M1, M2, M3, M4 and M5 for full step, half step, ¼ step, 1/8 step, 1/16 step and 1/32 step respectively. To achieve maximum possible accuracy, M5 mode is selected with 1/32 step.

For stepper motor 1 (Link1):

I revolution (360˚) = 200×32 = 6400 steps

1˚ = 6400/360 = 17.778 steps.

For stepper motor 2 (Link2):

Reduction ratio = 0.5

1 revolution (360˚) = 2×200×32 = 12800 steps

1˚ = 12800/360 = 35.556 steps.

For stepper motor 2 (Vertical axis):

Lead screw pitch = 2 mm

Number of starts = 4

Lead = 8 mm

Thus, 1 mm = 1/8 revolution = 6400/8 = 800 steps.

7. INTER-STEP DELAY

To make sure that the stepper motor operates smoothly it is necessary to accelerate and decelerate the stepper motor while starting and stopping.

It can be seen from fig-8 that a linear speed increase can be obtained using constant acceleration or deceleration [8].

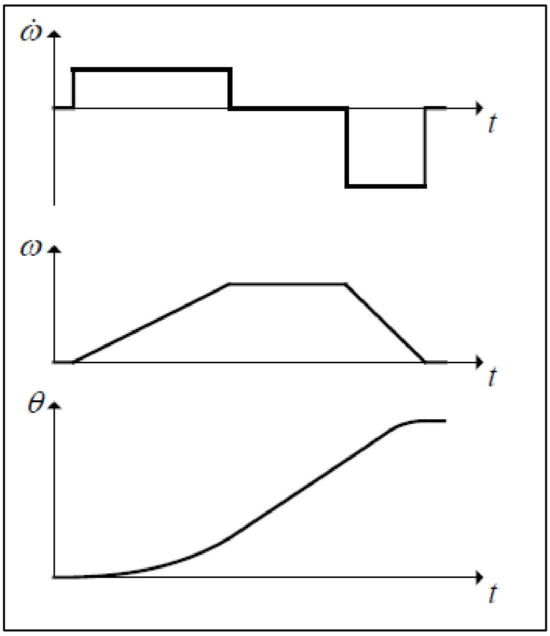

Fig - 8: Acceleration, Speed and Position.

Stepper motor speed is controlled by the time delay δt between each stepper pulse. It is essential to calculate these delays to make the speed of the stepper motor to follow the desired speed slope [6].

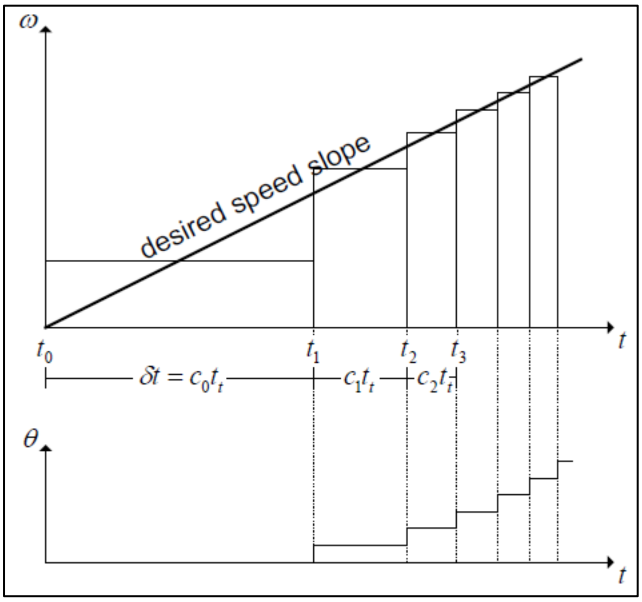

Fig - 9: Speed profile against stepper pulses

The first counter delay c_0 is given as,

$$c_0 = \frac{1}{t_t}\sqrt{\frac{2\Phi}{\dot{\omega}}}$$

and the nth counter delay c_n is given as
$c_n = c_0\left(\sqrt{n+1} - \sqrt{n}\right)$

where,

$$\Phi = \frac{2\Pi}{\text{steps per revolution}}\ \text{rad}$$

$$\omega = \frac{\Phi}{\delta t}$$

Owing to the limited computational power of microcontrollers, it is necessary to simplify the equations since it may take some time to compute two square roots.

Hence, using Taylor series approximation,

$$\sqrt{1 \pm \frac{1}{n}} = 1 \pm \frac{1}{2n} - \frac{1}{8n^2} + 0\left(\frac{1}{n^3}\right)$$

Therefore,

$$\frac{c_n}{c_{n-1}} = \frac{c_0(\sqrt{n-1} - \sqrt{n})}{c_0(\sqrt{n} - \sqrt{n-1})} = \frac{1 + \frac{1}{2n} - \frac{1}{8n^2} + 0\left(\frac{1}{n^3}\right) - 1}{1 - \left(1 - \frac{1}{2n} - \frac{1}{8n^2} + 0\left(\frac{1}{n^3}\right)\right)} = \frac{4n-1}{4n+1}$$

The expression for counter delay can be approximated as:

$$c_n = c_{n-1} - \frac{2c_{n-1}}{4n+1}$$

The time required by the microcontroller for this calculation is much less than the double square root, but when n = 1, an error of 0.44 is introduced. To compensate this error, c_0 can be multiplied by 0.676.

5. ELECTRONICS

Since the objective of the research is to make robots available for day to day use, an open source, easily reprogrammable and is readily available microcontroller is needed. Arduino UNO meets all the requirements. A CNC shield is used along with three DRV8825 motor drivers to drive the stepper motors individually. This CNC-shield can be mounted directly over the Arduino board. The motor driver enables to micro step the stepper motor down to 1/32-step [9]. This helps in increasing the accuracy. Three limit switches are used for referencing the robotic arm. This eliminates the need for rotary encoders. The Arduino board is powered by 5V DC power supply while the stepper motors are powered by 12V DC power supply. The Arduino board is connected to a computer via serial communication [10].

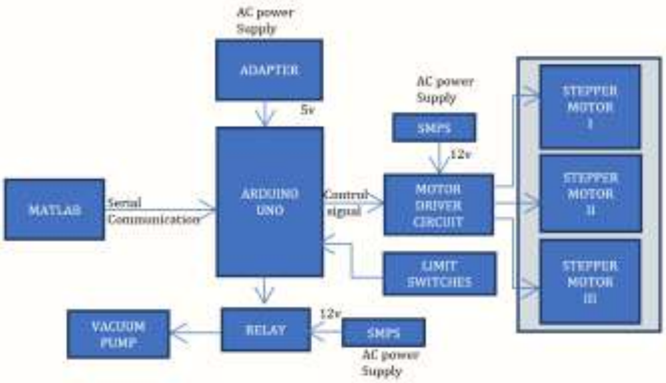

Fig - 9: Block diagram of SCARA robot

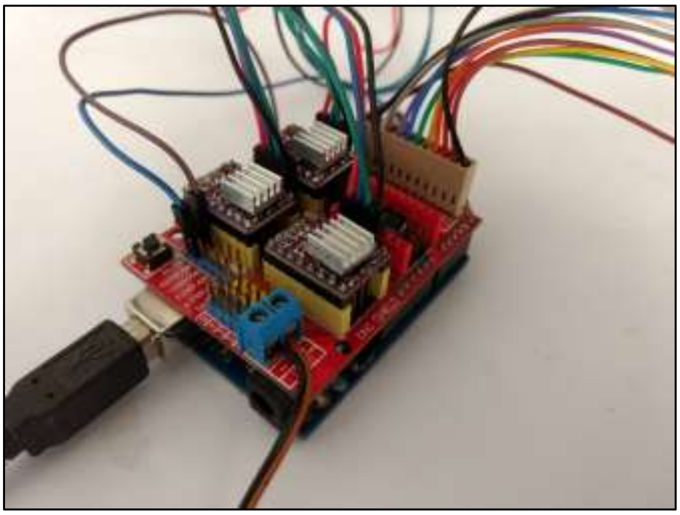

Fig - 10: Electronic Circuit of SCARA robot

6. SOFTWARE

The graphical user interface required to control the robot is designed using MATLAB. Since the processing power of microcontroller is limited, all the calculations are performed using MATLAB software. It converts the Cartesian coordinates (Px, Py) into link angles θ1 and θ2. Further, these angles are converted into steps. These number of steps are sent to the microcontroller using serial communication. The robotic arm can be operated in manual or auto mode. To use the manual mode, the user enters the desired cartesian coordinates. After entering the coordinates and clicking update, it will move the end effector to the desired location. Vacuum pump can be switched on and off using the provided buttons. In the auto mode, the user is required to record the sequence of operation by entering the coordinates, the dwell time, and the speed as 0-100%. In auto mode, this recorded sequence can be executed either in a loop or wait after execution. Since rotary encoders are not used, it is necessary to reference the robotic arm every time it is started using the special function in the software. Whenever the auto mode is interrupted or stopped, it should be referenced again. A status bar at the bottom of the GUI shows the current state of the robotic arm. Fig - 11 shows the graphical user interface that is used to communicate with the microcontroller.

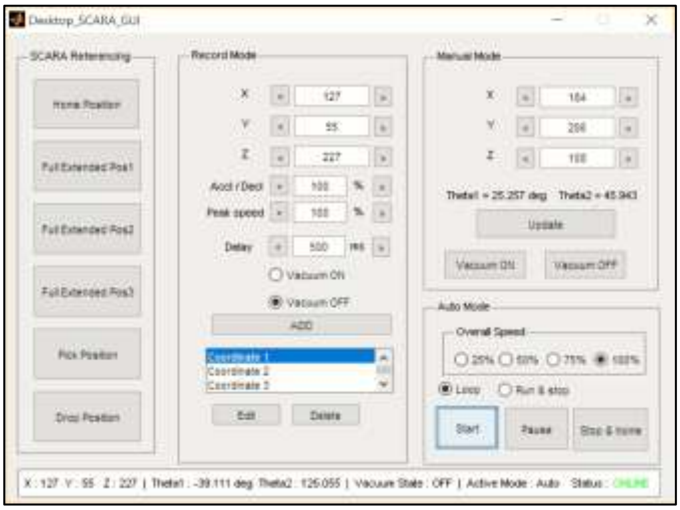

Fig - 11: Graphical User Interface

7. TRIALS

The precision of the robotic arm is tested with the help of a dial gauge having least count of 10 microns. The gauge is placed in such a way that the probe of dial gauge touches the arm [11, 12]. Subsequently the gauge was preset to zero. The setup is shown in fig 12.

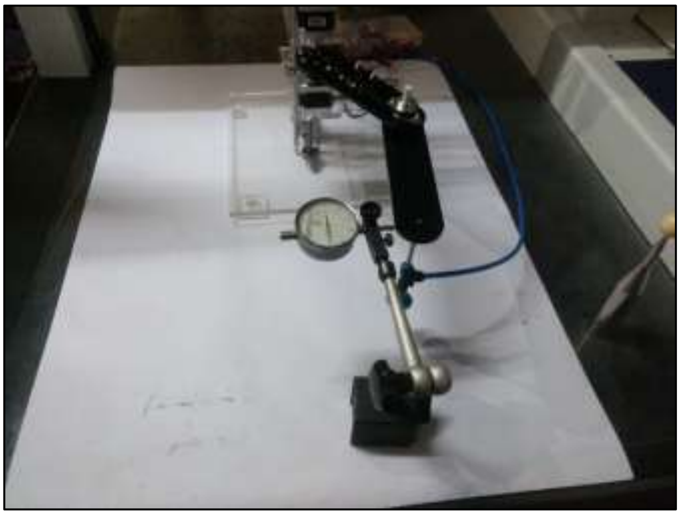

Fig - 12: Setup for repeatability trials

After performing series of movements, the arm was brought to the same coordinate and the dial gauge readings was noted. Ten such trials were conducted, and the average repeatability of 0.1 mm was observed. Fig – 13 a and b demonstrate a sample reading.

Fig – 13 (a): 0 micron

Fig – 13 (b): 100 microns

7. CONCLUSION

A 3 DOF SCARA robot is designed and developed for carrying out day to day applications like pick and place. The robot is first modelled in Inventor to get the values of weight and inertia for stepper motor selection. The robotic arm is then assembled using off the shelf parts to reduce the cost of the robot. The end effector attachment is so designed so that it can be modified according to requirements. Arduino UNO is used along with motor drivers to control the robotic arm. The stepper motor drivers enable the stepper motors to be micro stepped to 1/32-step to increase accuracy. A specially designed GUI using MATLAB serves as a human machine interface and also converts cartesian coordinates to SCARA angles. The GUI can record sequence of operations and execute the sequence as per the need of the user. An algorithm for accelerating and decelerating stepper motors is introduced to ensure smooth working of the robot even at high speeds. Finally, the robot is tested for repeatability and is found to be within 0.1 mm which is within acceptable limits.

8. FUTURE SCOPE

Presented research uses coordinates entered by the user as input and records the sequence. Further a camera can be used to capture the real time environment and with the help of image processing, the robotic arm can determine the coordinates to pick and place objects [13]. Furthermore, various control modes such as joystick, mouse, gesture, etc. can be used to control the robotic arm. The presented arm uses limit switches for referencing. Using rotary encoders will eliminate the need of limit switches and provide good positional accuracy [14]. The robotic arm is designed to accommodate different types of end effectors. Such different end effectors can be developed and tested on this SCARA robot. Attaching an extruder to the end effector can enable this robotic arm to 3D print objects with the help of provided STL file. With the help of a laser engraver, this SCARA robot can be used for laser engraving on surfaces such as wood, acrylic, cardboard etc. A dedicated microcontroller and software can be developed to compute faster and thereby increase the speed of the SCARA robot [15].

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