

# Design and Development of Stepper Motor Based XY Scanning Stage

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**ABSTRACT:** Precision planar motion (XY) stages are widely used in semiconductor manufacturing systems, precision machine tools, and scanning probe measurement systems. This research presents a design, modeling, manufacturing and system interfacing of Stepper Motor based XY Scanning Stage for precision application. Serially mounted XY stage is initially modeled using modeling software CATIA V5 and further analysis is carried out in ANSYS 14. Once design was within acceptable limit it is further taken for manufacturing and entire XY stage is manufactured. Mounting of Stepper is ensured by providing appropriate tolerances during manufacturing. Designed stage consists of two bipolar Stepper Motor coupled with a lead screw as a feed drive by means of aluminium flexible coupling. These Stepper Motors are further interfaced with PC via Arduino Microcontroller board. To control the movement of XY Scanning Stage, Arduino programming is done with the Arduino Motor Shield board. This XY Scanning Stage finds various precision micro positioning applications such as in 3D printers and precision machine tools.

**KEYWORDS:**3D Printer, Arduino, Stepper Motor, XY Scanning Stage.

## I. INTRODUCTION

The XY stage, which is composed of a motion mechanism driven by actuators for moving an object in the XY plane, is a fundamental component of a positioning system used in industries such as micromachining and scanning probe microscopy [1]. Many of the state-of-the-art ultra-precision XY stages have a stage motion mechanism composed of air-bearing or roller-bearing supported linear slides, which are driven by linear motors. Laser interferometers or linear encoders are often used as the feedback sensors. While the conventional XY stage is stacked up by two linear stages composing of many components, such as ball screw, bearing, linear slide, etc. [2]

Efforts have been made to develop the state-of-the-art XY micro-stages, in which flexure hinge mechanisms are employed as the stage motion mechanisms. Piezoelectric actuators (PZTs) have often been employed as the actuators. Rong-Fong et al. have developed a micro/nano-meter XY precision positioning table, in which the coarse and fine positioning are performed by the permanent magnet synchronous motor (PMSM) and piezoelectric actuator (PA), respectively [3]. Dongwoo Kang et al. have proposed compact high precision XY-scanner providing nanometer-level resolution and a millimeter-level travel range composed of a voice coil motor (VCM) and double compound linear spring flexure guide mechanism[4]. Yuki Shimizu et al. have designed XY micro-stage which consists of two PZTs and a friction component made by permanent magnet is mounted on the centre of the stage base for driving the stage moving plate made by steel in the X- and Y-directions based on a friction drive. Leaf springs are employed to guide the X- and Y-directional motions of the moving plate over a range of  $\pm 1$  mm in both directions [1]. Chien-Hung Liu et al. have presented a Dual-Axis Long-Travelling Nano-Positioning Stage (DALTNPS). In order to extend the travelling and increase the accuracy, the two sorts of stages, a traditional ball-screw stage and a three-degrees-of-freedom (3-DOF) piezo-stage, were composed. The traditional ball-screw stage which is composed of two guide-ways and a ball-screw at each axis is a long-travel stage, and the 3-DOF piezo-stage, which is composed of three piezoelectric actuators and four translation-rotation mechanisms, is a high precision stage [5]. Kuang-Chao Fan et al. have developed an innovative

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Vol. 4, Issue 9, September 2015

CMM design, including the arch-bridge, theco-planar precision XY-stage composing of many components, such as ball screw, bearing, linear slide, etc. The long travel of each axis is activated by the piezo-ceramic ultrasonic motor with its AC drive mode. The table is moved along the precision ground rod of the frame in the X-direction, and the frame is moved in the Y-direction along the precision ground rod of the base [6].

The motivation of this research is to develop a precision XY micro-stage that has a millimeter level travel range with positioning resolution upto 10 microns. A friction drive mechanism such as lead screw and nut is expected to achieve a long-travel-range stage motions with the permanent magnet step motors instead of employing short-stroke PZT actuators. As compared to the PZT and other electromechanical actuators stepper motor implementation provides cheap way to get the work done. While the PZT and electromechanical actuator features expensive designs and are focused in precision. Stepper motor is a synchronous DC motor that uses electromagnetic properties to convert digital pulses into mechanical rotation. It is composed by windings, so that when energized in order, provide movement in steps. To control the X and Y motions the Arduino Mega 2560 microcontroller is used which is a cost effective way to achieve required amount of travel range. The motion stages are driven by lead screws with the guide rods and linear motion bearing supports. By providing number of steps, speed and the input pin number and direction, a control over the motion stages is developed via Arduino programming.

## II. DESIGN OF THE STEPPER MOTOR BASED XY SCANNING STAGE

### A. Design modelling

The XY stage is modelled using modelling software CATIA V5. CATIA Version 5 uses the Sketcher workbench as its principal method is to create profiles. These profiles can be constrained using many different types of constraints. The entire stage as shown in fig.1 is assembled considering the design constraints. This XY stage is the combination of two stage platforms along X and Y directions. These stages are assembled in CATIA V5 considering the axis coincidence, contact and offset constraints.

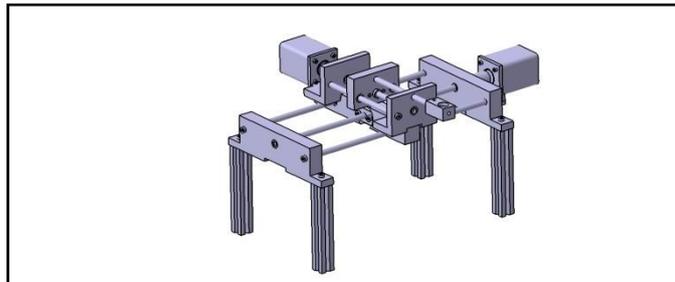


Fig.1. CAD model of XY stage in CATIA V5

### B. Finalized Assembly

The X-Y scanning stage consists of two motion stages. The Y axis stage sits upon three rods located in between the two side support plate, here the three rods are the two guide rods and the lead screw, the lead screw located at the middle of guide rods allows linear motion of the X stage along the rods axis. A stepper motor drives a shaft that is coupled to the lead screw with a motor coupler on one side of the Y axis, allowing it to move the Y stage platform along with the X stage mounted on it. The X axis stage consists of three rods as two guide rods and lead screw. Here, the X stage is located in between the two side plates to restrict the linear motion of X stage through X axis which are mounted on the Y stage platform. Another stepper motor drives the lead screw along with the X stage along the X axis. The entire XY stage assembly is resting on the support rods of squared and grooved cross section made of Aluminium. Detailed components are shown in fig.2 (a) and (b).

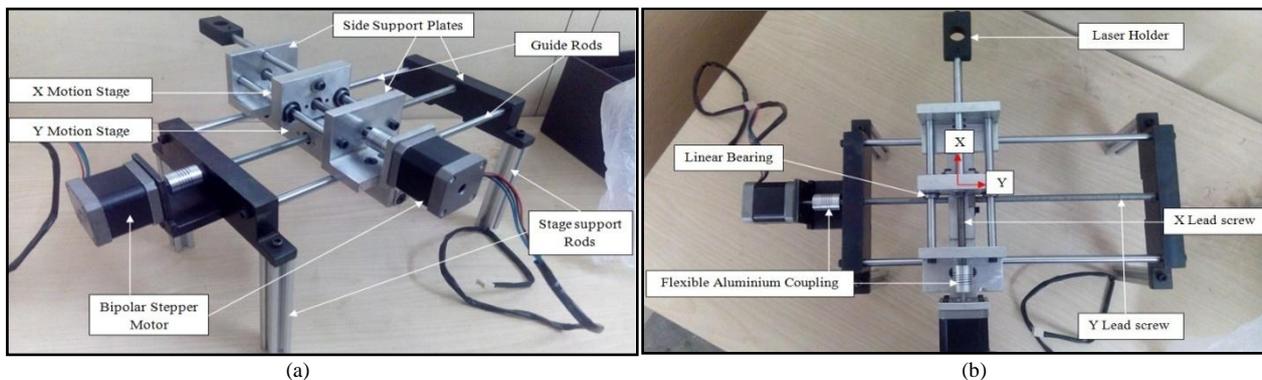


Fig.2 (a) and (b). Assembly of Stepper Motor based XY Micro stage

### C. Design Considerations for feed drive mechanism

#### (1) Design of Lead Screw

The lead screw selected for our purpose is of following characteristics according to IS: 4218 (Part III) 1976 [10].

a) *Screw Starts*: This is the number of independent threads on the screw shaft. The lead screw selected here is a single start. For a single start screw, lead & pitch are the same.

b) *Pitch*: It is the distance along the screw axis from a point on one thread to a corresponding point on the adjacent thread. Here pitch = 1.25mm

c) *Lead*: It is the distance the nut advances along the screw in one revolution.

Lead = pitch x number of starts

$$= 1.25 \times 1$$

$$= 1.25 \text{ mm}$$

d) *Major Diameter* =  $d = 8 \text{ mm}$

e) *Minor (core) Diameter* =  $d_c = 6.466 \text{ mm}$

f) *Direct compressive stress due to axial load*:

The body of a screw is subjected to an axial force  $W$  and torsional moment ( $T$ ). The direct compressive stress  $\sigma_c$  is given by,

$$\sigma_c = W / [(\pi/4) \times d_c^2]$$

Maximum axial load induced by the stepper motor ( $W$ ) = 10N

$$= (10 \times 4) / (\pi \times 6.466^2)$$

$$\sigma_c = 0.3045 \text{ MPa}$$

g) *Shear Stress Due to motor torque*:

The torsional shear stress is given by,

$$\tau = 16T / (\pi \times d_c^3)$$

Here  $T$  = motor torque = 4.4 kg.cm = 0.43164 Nm

$$= (16 \times 0.43164) / (\pi \times 0.006466^3)$$

$$= 8.1317 \text{ MPa}$$

h) *To find the principal stresses*

Maximum principal stress (tensile or compressive)

$$\sigma_{c(\max)} = 1/2 [\sigma_c + \sqrt{(\sigma_c^2 + 4\tau^2)}]$$

$$= 0.5 [0.3045 + \sqrt{(0.3045^2 + 4 \times 8.1317^2)}]$$

$$= 8.45 \text{ MPa.}$$

i) *Maximum shear stress*

$$\tau_{(\max)} = 1/2 [\sqrt{(\sigma_c^2 + 4\tau^2)}]$$

$$= 0.5 [\sqrt{(0.3045^2 + 4 \times 8.1317^2)}]$$

$$= 8.1331 \text{ MPa}$$

j) *Check for Safety*

Assume Factor of safety,  $S_f = 2$ , for steel material and subjected to external static forces (1.5 to 2 based on yield strength of material).

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$$(\sigma_c)_{all} = S_{yc}/S_f$$

Where,  $S_{yc}$  = yield strength =250 MPa (for steel lead screw)  
= 250/2

$$(\sigma_c)_{all} = 125 \text{ Mpa}$$

As  $(\sigma_c)_{all} >> \sigma_c (\text{max})$

Lead screw is safe

Allowable Shear stress is given by,

$$\tau_{all} = S_{sy}/S_f$$

Where,  $S_{sy}$  = Yield strength in shear =0.5  $S_{yc}$   
= 125/2

$$\tau_{all} = 62.5 \text{ MPa}$$

As  $\tau_{all} >> \tau_{max}$

Lead screw is safe in Shear.

### 2) Design of Nut

Major Diameter =  $d = 8 \text{ mm}$

Core Diameter =  $d_c = 6.647 \text{ mm}$

#### a) Height of Nut (H)

The bearing pressure between the contacting surfaces of the screw and the nut is an important consideration in design.

Therefore,

$$P_b = W / [(\pi/4) \times (d^2 - d_c^2) \times n]$$

Where,  $P_b$  = unit bearing pressure (N/mm<sup>2</sup>)

$n$  = Number threads in contact

$$0.085 = 10 \times 4 / [\pi \times (8^2 - 6.647^2) \times n]$$

(Assume  $P_b = 0.085 \text{ MPa}$  for nut)

$$n = 7.56 = 8$$

Height of nut,  $h = n \times p$

Where  $p$  = Pitch of threads

$$h = 8 \times 1.25$$

$$h = 10 \text{ mm}$$

#### b) Check for the stress in the nut

The threads of the screw which are engaged with the nut are subjected to transverse shear stresses. The screw will tend to shear off the threads at the core diameter under the action of load  $W$ . The shear area of one thread is  $\pi d_c t$ . The transverse shear stress in the screw is given by,

$$\tau_{(nut)} = W / \pi d_c t$$

Where,  $t$  = Thickness of screw =  $p / 2 = 1.25 / 2 = 0.625 \text{ mm}$

$$= 10 / (\pi \times 8 \times 8 \times 0.625)$$

$$\tau_{nut} = 0.0796 \text{ MPa}$$

As  $\tau_{all} >> \tau_{nut}$  Nut is safe.

### D. FEA Analysis on Lead screw and Nut

At first, the modelling of lead screw and nut is done in CATIA-V5. After that it is imported in the ANSYS 14 workbench. A static structural analysis is done with this model. Material properties for the stainless steel M8 lead screw and nut assembly as in table I with proper boundary conditions are applied and then final results are obtained after solution conversions.

TABLE I. MATERIAL PROPERTIES OF LEAD SCREW AND NUT ASSEMBLY

| Material properties                | Data entered             |
|------------------------------------|--------------------------|
| Tensile/compressive Yield strength | 250 MPa                  |
| Young's modulus                    | $2 \times 10^5$ MPa      |
| Poisson's ratio                    | 0.3                      |
| Bulk Modulus                       | $1.6667 \times 10^5$ MPa |
| Shear Modulus                      | 76923 MPa                |

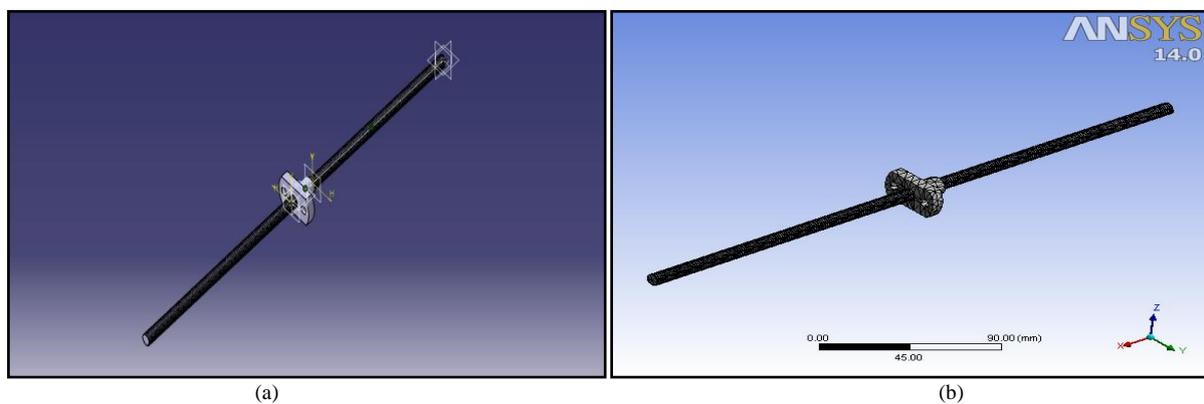


Fig.3 (a) CAD Model of lead screw and nut assembly in CATIA V5. (b) Meshed model of lead screw and nut assembly in ANSYS 14.

A M8 lead screw with nut is assembled in the CATIA V5 workbench as in fig 3(a). This model is imported in the ANSYS 14 workbench for further analysis. A frictional contact is created in the screw and nut section and fine meshing is done on the model as shown in fig 3(b).

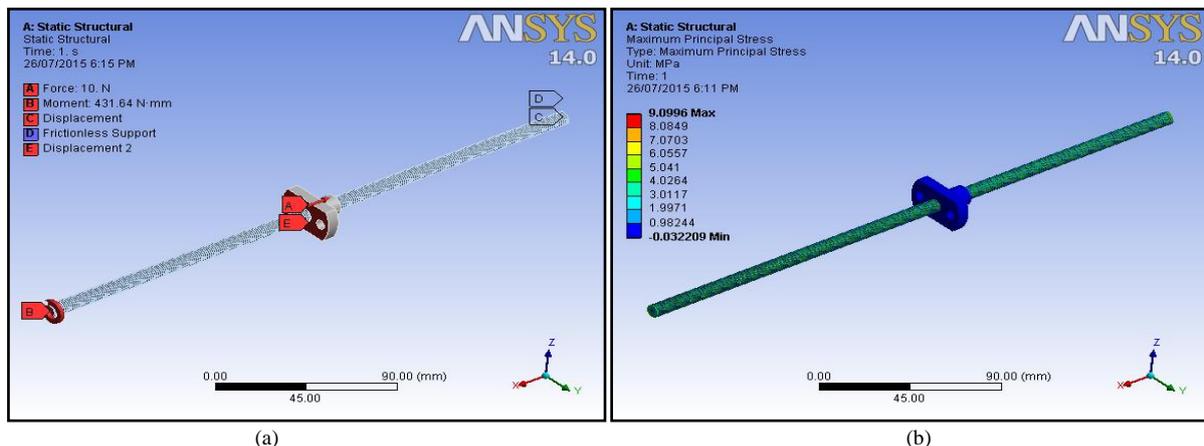


Fig.4 (a) Boundary conditions of lead screw and nut assembly in ANSYS 14. (b) Maximum principle stress from ANSYS 14.

A frictional contact is created between the lead screw and nut with coefficient of friction of 0.2. At one end the moment of 431.64 N.mm is applied while at the other end frictionless support is given. A force of 10 N is applied axially on the nut surface exerted by the motor. The Y and Z axis motion is restricted while the X axis kept free. These boundary conditions are shown in fig 4(a). From this data a solution is prepared for maximum principal stress as in fig. 4(b).

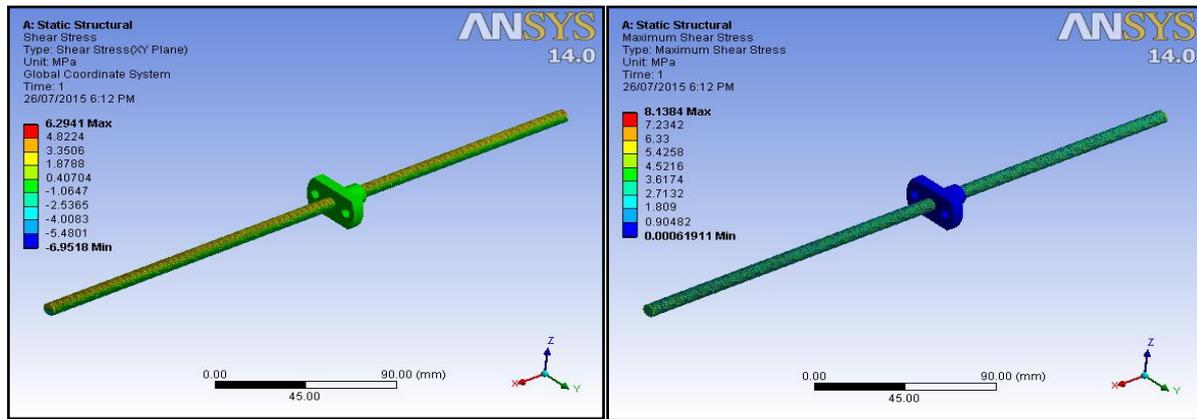


Fig.5 (a) Shear stress from ANSYS 14. (b) Maximum Shear stress from ANSYS 14.

Further the shear stress due to motor torque is identified in solution information as in fig. 5(a). Maximum shear stress areas are also identified as in fig. 5(b)

**E. Results from the FEA analysis**

The following table II shows the results comparison from analytical and ANSYS simulation

TABLE II. RESULTS FROM THE ANALYTICAL AND FEA ANALYSIS

| Results                        | Analytical calculations | FEA simulation |
|--------------------------------|-------------------------|----------------|
| Maximum principle stress (MPa) | 8.1331                  | 9.0996         |
| Shear stress (MPa)             | 8.1317                  | 6.2941         |
| Maximum Shear stress (MPa)     | 8.45                    | 8.1384         |

The values obtained from analytical calculations and FEA, are within the acceptable limits thus the lead screw and nut selected for our application is safe.

**III. MECHATRONICS INTERFACING**

The NEMA 17 stepper motor is connected to an easy driver motor controller board which is controlled by an Arduino Mega2560 microcontroller by means of wire connections as shown in block diagram of fig.6. This system is an open loop control system.

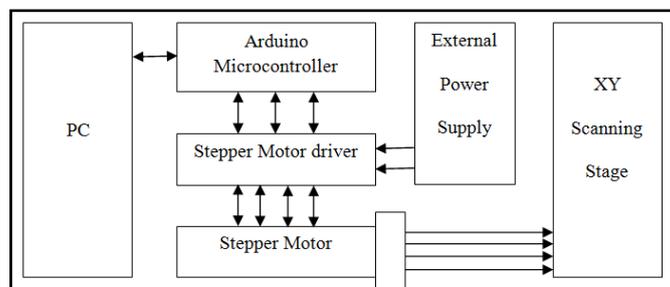


Fig.6 Block diagram of computer interfacing of XY Scanning Stage

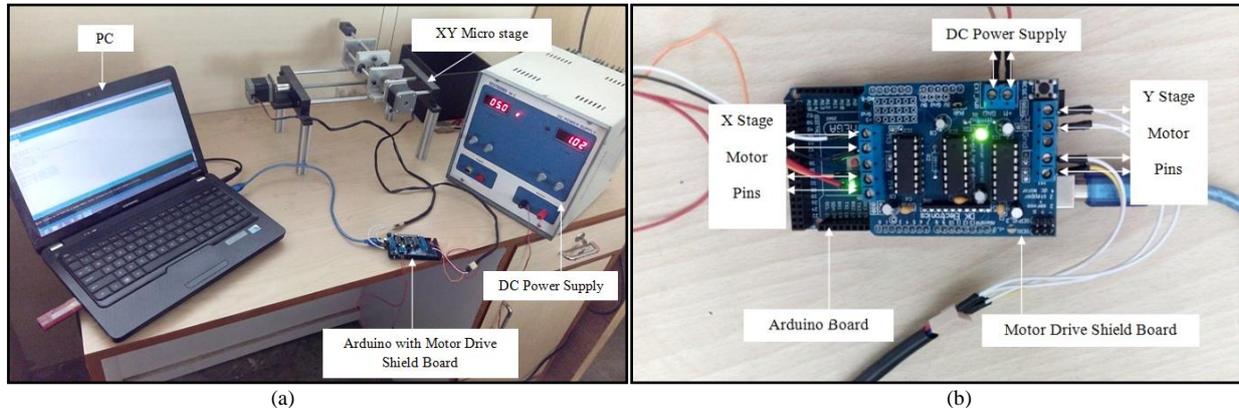


Fig.7 Mechatronics Interfacing (a) The XY stage interfaced with PC (b) Wire connections for the Arduino Shield board

Fig. 7(a) shows the XY stage interfacing with PC. The Arduino program is uploaded in the microcontroller which controls the number of pulses to be generated for the stepper motor provided with a required amount of voltage level by means of Arduino shield motor board as shown in fig 7(b). By defining the ports where the stepper motors are connected controller initializes the Arduino stepper library. Setting the motor speed with varying number of steps, a control is developed with the motion direction.

#### IV. EXPERIMENTAL RESULTS

Once the Arduino programming is done and as soon as the upload button is pressed the XY stage is ready to go accordingly. Using the Arduino motor shield board with a forward- backward programming the X and Y motion stages translated according to the steps given in the program. Here the stepper motor has 1.8° step angle means when it completes one revolution, the number of steps taken by stepper motor are  $360/1.8=200$  steps. In one complete revolution of stepper motor the distance travelled is equal to the pitch of the lead screw. Here the pitch of lead screw is 1.25mm. Thus in 200 steps the distance travelled is 1.25 mm. Using this terminology the calculations regarding the distance travelled by the motion stages for a given number of steps in the program gets easier.

Now a simple experiment is done to measure the travelled distance with a digital dial indicator instrument. The pointer of dial is rested on the one of the flat surface in the direction parallel to the motion of platform as in fig.8. The forward and backward movement is controlled with an Arduino program with a number of steps and speed. Measurements were taken for 200 RPM with varying number of steps from 100 to 2000 for each stage.

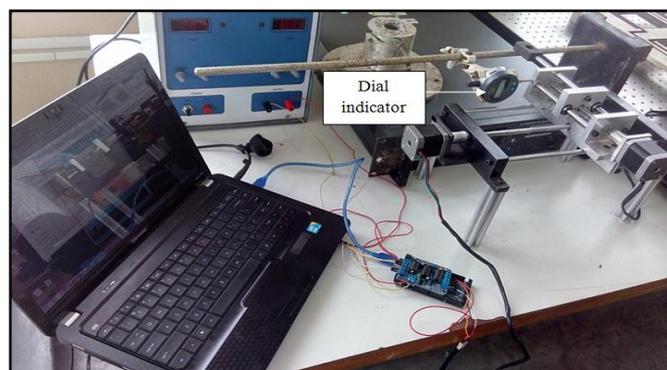


Fig.8 The experimentation with dial indicator

From the values obtained graphs were plotted against the number of steps on X axis with observed and expected values on Y axis as shown in fig.9. It is observed from the graphs that the X motion stage values as in fig. 9(a) are

much closer to expected values than the Y motion stage values as in fig. 9(b). Table III shows the motion observed with varying number of steps at speed of 200 rpm.

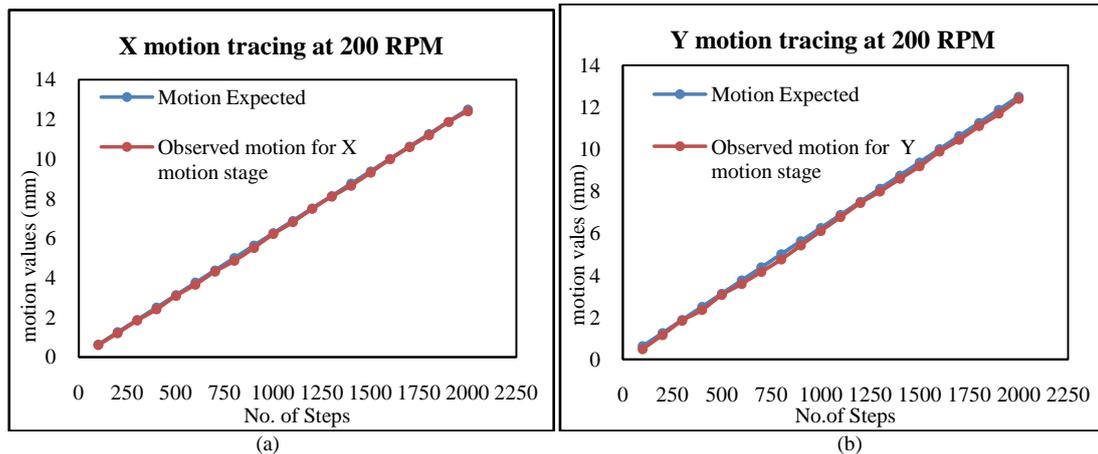


Fig.9 Graph of the expected and observed motions of the (a) X motion stage (b) Y motion stage

TABLE III. RESULT INTERPRETATIONS FROM EXPERIMENTATION

| No. of steps | Motion expected (mm) | Observed stage motion readings at 200 RPM |                    |
|--------------|----------------------|---|--------------------|
|              |                      | For X motion stage                        | For Y motion stage |
| 100          | 0.625                | 0.598                                     | 0.485              |
| 200          | 1.25                 | 1.198                                     | 1.154              |
| 300          | 1.875                | 1.835                                     | 1.843              |
| 400          | 2.5                  | 2.398                                     | 2.346              |
| 500          | 3.125                | 3.08                                      | 3.062              |
| 600          | 3.75                 | 3.65                                      | 3.586              |
| 700          | 4.375                | 4.305                                     | 4.165              |
| 800          | 5                    | 4.85                                      | 4.745              |
| 900          | 5.625                | 5.5                                       | 5.425              |
| 1000         | 6.25                 | 6.205                                     | 6.105              |
| 1100         | 6.875                | 6.8                                       | 6.765              |
| 1200         | 7.5                  | 7.48                                      | 7.438              |
| 1300         | 8.125                | 8.098                                     | 7.985              |
| 1400         | 8.75                 | 8.65                                      | 8.59               |
| 1500         | 9.375                | 9.305                                     | 9.185              |
| 1600         | 10                   | 9.98                                      | 9.88               |
| 1700         | 10.625               | 10.6                                      | 10.44              |
| 1800         | 11.25                | 11.2                                      | 11.09              |
| 1900         | 11.875               | 11.869                                    | 11.68              |
| 2000         | 12.5                 | 12.402                                    | 12.385             |

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Vol. 4, Issue 9, September 2015

## V. CONCLUSION

The XY Scanning Stage is micro-positioning stage which is driven by two bipolar stepper motors and controlled by Arduino Mega2560 microcontroller. We have designed and developed this XY Scanning Stage to precisely position the motion stage platforms along the predefined directions given by the special programs developed using Arduino software. The values obtained from the experimental results are within the acceptable limits.

Generally, the XY stages are used in precision positioning industries. They can also find the applications in micromachining, micro fabrications, and stereo- lithographic tables. This developed XY stage Scanning Stage is definitely beneficial in such micromachining applications as laser cutting, scanning profiles or geometries.

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