Design and Development of a Low Cost XYZ Positioning Control System(3D Printer)

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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 XYZ Positioning System for precision application. Serially mounted XYZ 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 XYZ 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 XYZ Positioning, Arduino programming is done with the Arduino Motor Shield board. This XYZ Positioning Control System finds various precision micro positioning applications such as in 3D printers and precision machine tools.

KEYWORDS: 3D Printer, Arduino, Stepper Motor, XYZ Positioning Control Ssystem, Lead Screw.

I. INTRODUCTION

The XYZ stage, which is composed of a motion mechanism driven by actuators for moving an object in the XYZ 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 XYZ 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 XYZ 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 XYZ 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 millimetre-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 ±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 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 XYZ POSITIONING CONTROL SYSTEM

A. Design modelling

The XYZ 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 three stage platforms along X,Y and Z directions. These stages are assembled in CATIA V5 considering the axis coincidence, contact and offset constraints.

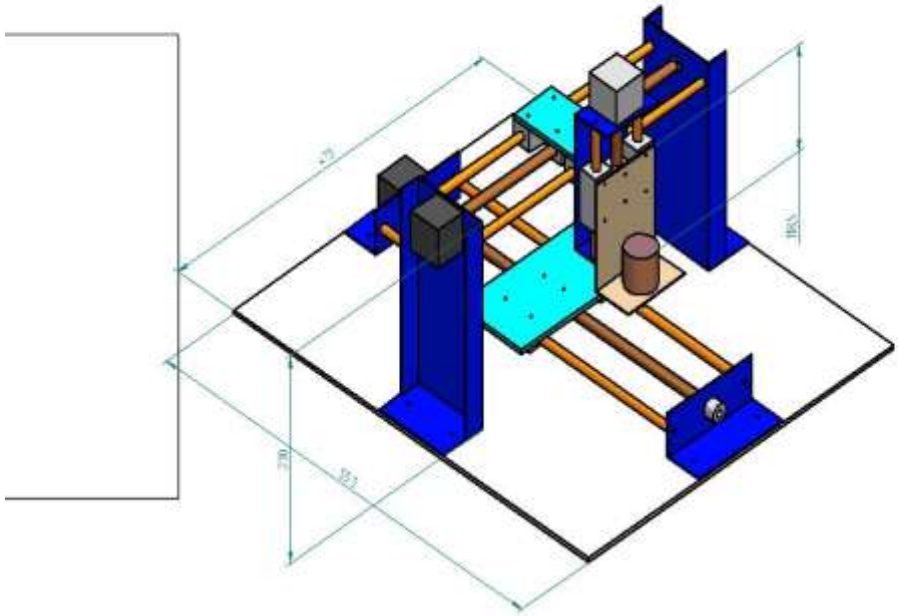

Fig.1. CAD model of XYZ stage in CATIA V5

B. Finalized Assembly

The XYZ scanning stage consists of three 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 XYZ 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).

Fig.2 (a) 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 =1.25mm

d) Major Diameter =d= 8 mm

e) Minor (core) Diameter = dc=6.466 mm

f) Direct compressive stress due to axial load:

The body of a screw is subjected to an axial force Wand torsional moment (T).The direct compressive stress σ_c is given by,

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

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

$= (10\times4) / (\pi\times6.466^2)$

σ_c= 0.3045 MPa

g)Shear Stress Due to motor torque:

The torsional shear stress is given by,

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

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

$= (16\times0.43164) / (\pi\times0.006466^3)$

= 8.1317 MPa

h) To find the principal stresses

Maximum principal stress (tensile or compressive)

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

$=0.5[0.3045+\sqrt{(0.3045^2 +4\times8.1317^2)}]$

= 8.45 MPa.

i) Maximum shear stress

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

$=0.5[\sqrt{(0.3045^2 +4\times8.1317^2)}] =$

8.1331 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).

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

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

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

As $(\sigma_c)_{all} >> \sigma_{c\,(max)}$

Lead screw is safe

Allowable Shear stress is given by,
$\tau_{all}=S_{sy}/S_f$
Where, S_{sy} = Yield strength in shear
$=0.5\ S_{yc} = 125/2$
$\tau_{all} = 62.5$ MPa
As $\tau_{all} >> \tau_{max}$
Lead screw is safe in Shear.

2) Design of Nut

Major Diameter =d= 8 mm Core Diameter = dc=6.647 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,
$Pb=W/ [(\pi/4) \times (d^2 - dc^2) \times n]$
Where, Pb = unit bearing pressure (N/mm²) n = Number threads in contact $0.085=10\times4 /[\pi \times (8^2-6.647^2) \times n]$ (Assume P_b= 0.085 MPa for nut)
n= 7.56 = 8
Height of nut, h = n × p Where p = Pitch of threads h = 8×1.25
h=10 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 πdct. The transverse shear stress in the screw is given by,
$\tau_{(nut)}=W/ \pi ndt$
Where, t = Thickness of screw = p / 2=1.25/2=0.625mm =10/ (π×8×8×0.625)
τ_{nut}= 0.0796 MPa
As $\tau_{all} >> \tau_{nut}$ Nut 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 a open loop control system.

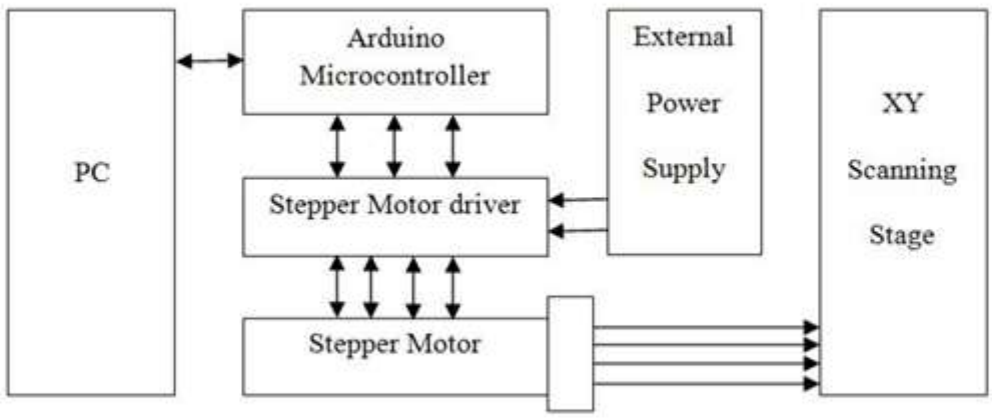

Fig.6 Block diagram of computer interfacing of XYZ Scanning Stage

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. 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.

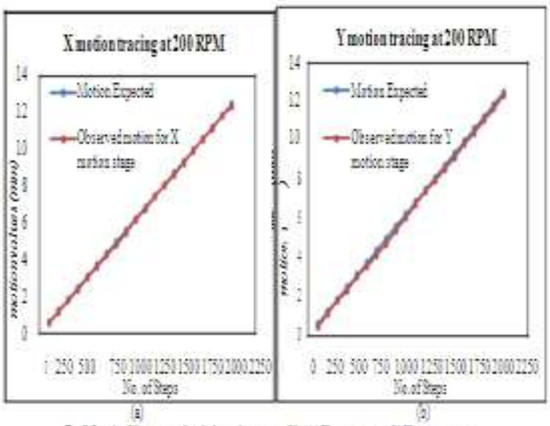

Fig.9 Graph of the expected and observed motions of the (a) X motion stage (b) Y motion stage

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

V. CONCLUSION

The XYZ Scanning Stage is micro-positioning stage which is driven by three bipolar stepper motors and controlled by Arduino Mega2560 microcontroller. We have designed and developed this XYZ 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 XYZ stages are used in precision positioning industries. They can also find the applications in micromachining, micro fabrications, and stereo- lithographic tables. This developed XYZ stage Scanning Stage is definitely beneficial in such micromachining applications as laser cutting, scanning profiles or geometries.

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