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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 paper presents a design, modeling, manufacturing and system interfacing of XY stepper motor based scanning stage for precision application. Serially mounted XY stage is initially modeled using modeling software CATIA V5. Its alignments and stress analysis is carried out by using ANSYS workbench. 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 aluminum flexible coupling. These stepper motors are further interfaced with PC via Arduino Microcontroller board. Experimental testing is carried out and orthogonality of axis is ensured by tracing X & Y direction. Orthogonality of axis is within the acceptable limit. To control the movement of XY stage, programming is done with the Arduino software. The accuracy within 10 microns is achieved with this stage for positioning. This XY Scanning Stage finds various precision micro positioning applications such as in 3D printers.

Keywords— **3D printers, Arduino Microcontroller, Orthogonality, XY Scanning Stage.**

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I. INTRODUCTION

High precision micro positioning technology is essential in applications such as scanning probing microscope, micro alignment, and micro fabrication. Such micropositioners are required to provide the motion in nanometer scales with high accuracy, speed, and load capacity [2]. Many of the 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 [1].

The basic function of a stage is to constrain motion to a defined direction. For a linear stage, this motion is, ideally, along a straight line. Motorized linear stages are used to precisely position objects along a single axis [5]. While implementing these XY stages various topologies can be found that are based in piezoelectric actuators, stepper motors and electromechanical actuators [4]. As compared to the PZT and other electromechanical actuators this 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 [3]. 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.

This research has two main steps. Step 1 is the development of a stage motion mechanism for the precision XY micro-stage. Step2 is the interfacing this mechanism with PC by means of an Arduino microcontroller along with a stepper driver circuit. The design features two bipolar

stepper motors to provide fully decoupled movement in each axis. The stage is guided by stainless steel rods for each stage. To move the stage, a lead screw is used to couple with the stepper motor by means of a flexible aluminum coupler. An Arduino Mega2560 is used as a microcontroller. To drive the motors, a stepper motor driver circuit is used and everything is powered by the Arduino (USB connection).

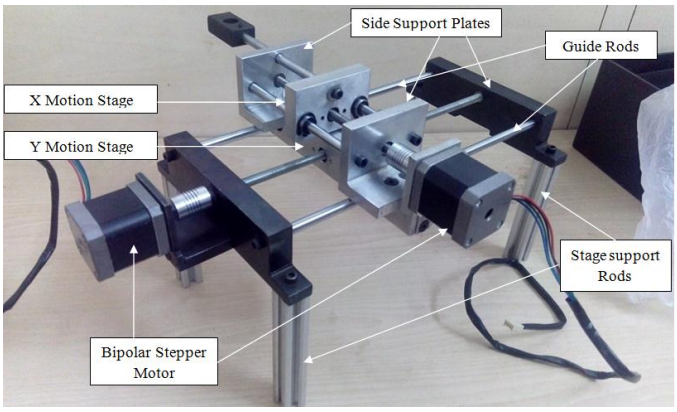
II. OBJECTIVES OF THE STUDY

The objective of this project is the development of XY Scanning Stage for micro positioning through PC based interfacing with Arduino microcontroller. The study incorporates the following implementations:

1. Design modeling of XY scanning stage in modeling software CATIA V5.
2. Stress analysis of model in ANSYS.
3. Fabrication of finalized design.
4. System interfacing with PC via Arduino board.
5. Motion control of the XY stage with Arduino programming.
6. Experimental testing by tracing X and Y direction.

III. HARDWARE DESIGN

Figure 1 shows, the X-Y scanning stage consists of two 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 also sits upon 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.



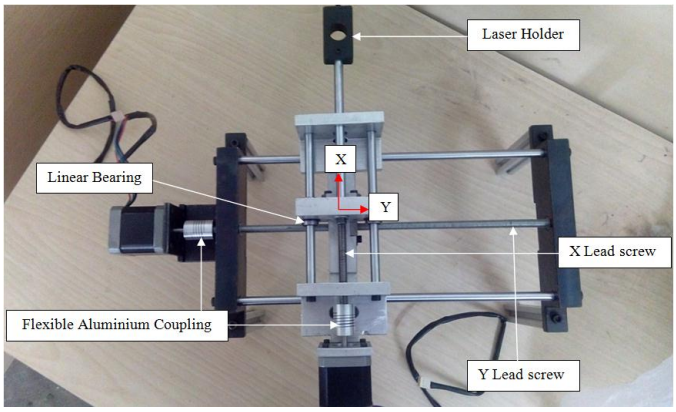


Fig.1 The XY Scanning Stage assembly

A. Design of Lead Screw

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

1) 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.

2) 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

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

Lead= pitch x number of starts

=1.25×1

=1.25mm

4) Major Diameter =d= 8 mm

5) Minor Diameter = dc=6.466 mm

6) Shear Stress Due to motor torque:

Shear Stress due to motor torque [10] is given by

$$\tau = \frac{16\ T}{\pi\ (d_c)^3}$$

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

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

τ = 8.1317 MPa

7) Direct compressive stress due to axial load:

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

$$\sigma_c = \frac{W}{\frac{\pi}{4}\ (d_c)^2}$$

= (10×4) / ($\pi \times 6.466^2$)

σ_c = 0.3045 MPa

8) To find the principal stresses

Maximum principal stress (tensile or compressive)

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

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

$\sigma_{c\,(max)}$ = 8.45 MPa.

Maximum shear stress

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

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

$\tau_{(max)}$ = 8.1331 MPa

B. Design of Nut

Major Diameter =do= 8 mm

Core Diameter = dc=6.647 mm

1) Height of Nut (H)

Allowable Bearing Pressure for Nut

$$P_b = \frac{W}{\frac{\pi}{4}[d_0^2 - d_c^2]n}$$

Where n = Number threads in contact

$$0.085 = \frac{10 \times 4}{\pi \times (8^2 - 6.647^2) \times n}$$

(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

2) Check for the stress in the nut

$$\tau_{(nut)} = \frac{W}{\pi n d_0 t}$$

Where, t = Thickness of screw = p / 2=1.25/2=0.625mm

$$= \frac{10}{\pi * 8 * 8 * 0.625}$$

$\tau_{(nut)}$= 0.0796 MPa

C. Design modeling

The XY stage is modeled using modeling software CATIA V5. The entire stage is assembled considering the proper axis alignments and surface constraints.

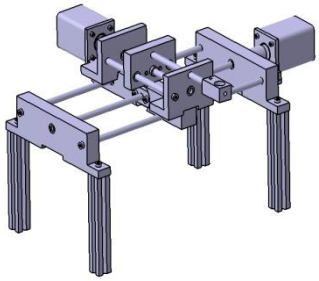


Fig.2 CAD model of XY stage in CATIA V5.

IV. SYSTEM INTEGRATION

The whole system of XY stage is composed of following main components. These are connected together so as to form a system which is further interfaced with PC and thereby a control is developed.

A. Stepper motor

Most of the application runs on servo motor, but accuracy cannot be maintained. So to maintain better accuracy stepper motor is chosen. There several types of stepper motor: they are hybrid synchronous stepper, variable reluctance stepper, permanent magnet stepper. Main two models are unipolar and bipolar stepper motor. In this paper, 4-wire bipolar motor of 1.8 degree step angle is used for better positioning and accuracy. Functioning of motor is based on stepping action. There are several stepping modes. They are full step, half step, micro step. Main consideration of stepper motor is torque and power rating. Based on the torque, load can be used for driving.

It is mounted on the mounting plates of both X and Y motion stages. The shaft of stepper motor is coupled with the lead screw by using flexible aluminum coupler. It controls the movement of lead screw in steps due to which we get precise movement of motion stages. Following are the specifications of stepper motor selected.

TABLE 1
STEPPER MOTOR SPECIFICATION

Motor Type	Bipolar Stepper
Step Angle	1.8°
Step Accuracy	5%
Holding Torque	4.4 Kg·cm
Maximum Speed	2344 RPM
Rated Voltage	12 V
Rated Current	2.4 A
Shaft Diameter	5 mm
Mounting Plate Size	NEMA 17
Number of Leads	4

B. The Arduino Board

According to the Arduino website [4], it is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. In simple terms, the Arduino is a tiny computer system that can be programmed with your instructions to interact with various forms of input and output. Arduino is composed of two major parts: the Arduino board, which is the piece of hardware and the Arduino IDE, the piece of software which runs on computer. It uses the IDE to create a sketch (a little computer program) that upload to the Arduino board. The sketch tells the board what to do.

1) The Arduino Hardware

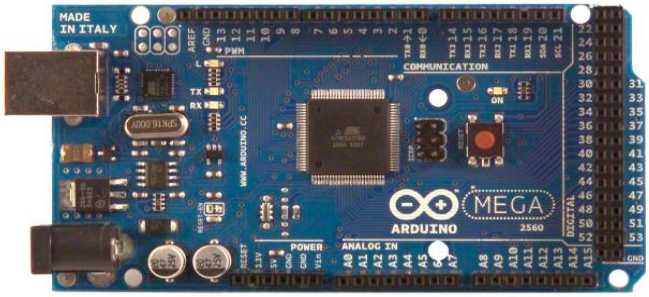


Fig.3 Arduino Mega2560 Microcontroller

The Arduino board is a small microcontroller board, which is a small circuit (the board) that contains a whole computer on a small chip (the microcontroller). The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

2) The Software (IDE)

The IDE (Integrated Development Environment) is a special program running on your computer that allows you to write sketches for the Arduino board in a simple language modeled after the Processing language. Actually, Arduino is an open source microcontroller board which can be programmed using free development software. The Arduino uses a simplified version of C/C++ programming language. With Arduino board, we can write a program to control physical systems by read and write analog/digital signal. Therefore, some analog sensors are needed to be connected to the Arduino to read analog signals, and the ADC (Analog

to Digital Converter) is the responsible to convert these signals to digital signals [9].

C. Easy Driver Stepper Motor Driver

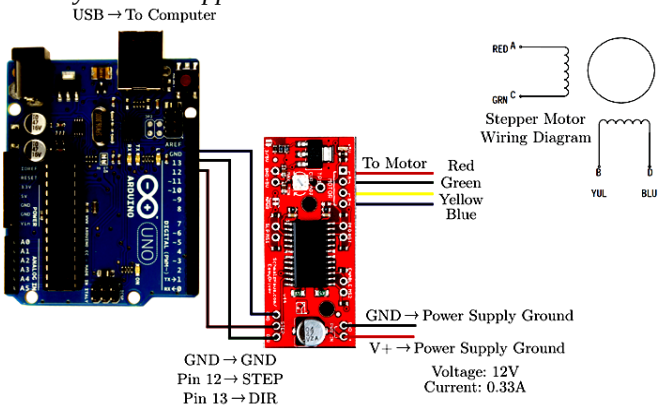


Fig.4 Easy driver stepper motor driver with Arduino

The Easy Driver is a simple to use stepper motor driver, compatible with anything that can output a digital 0 to 5V pulse (or 0 to 3.3V pulse if you solder SJ2 closed on the Easy Driver). The Easy Driver requires a 6V to 30V supply to power the motor and can power any voltage of stepper motor.

The Easy Driver has an on board voltage regulator for the digital interface that can be set to 5V or 3.3V. Connect a 4wire stepper motor and a microcontroller and you've got precision motor control! Easy Driver drives bipolar motors, and motors wired as bipolar. i.e.4, 6 or 8 wire stepper motors [6].

V. ARDUINO PROGRAMMING

In the XY Scanning Stage, we have to control the linear movement of the X and Y motion stage with the help of Stepper motor and lead screw. The stepper motors rotational motion is transformed in to linear motion with help of lead screw coupled with motor shaft. As the lead screw nut holds the motion stage, results in the movement of motion stage as lead screw translates.

As we have to control the movement of the motion stage, precisely and accurately we use Arduino microcontroller for precision and accuracy. The rotational movement of the stepper motor is controlled with the help of special Arduino program. The program mainly consists of various commands and statements to control the various parameters such as speed, time delay etc. [8]. Some calculations regarding the steps are as follows

Lead= pitch x number of starts

=1.25×1

=1.25mm

It means that in one rotation of lead screw the platform will travels by 1.25 mm.

Now,

Step angle = 1.8 degree

Steps per revolution = 200

One revolution = 200 steps =1.25mm linear motion stage in one rotation

1 step = 1/200 revolution = 0.005 mm linear motion of platform in one step.

Therefore we have to move the motion stage with 0.005 mm which results in better translation.

To test the XY scanning stage movement, we have developed a simple program that controls a stepper motor with the easy driver board. This results in the forward and backward spinning of stepper motor. A delay is set so that while reversing the direction, motor takes some time to proceed as per the program. Figure 6 shows the window of Arduino software in which the uploaded program is shown. After successful uploading, the red light turns on (as in fig.7) of the stepper driver and motor starts running.

VI. COMPUTER 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 figure 5. 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 easy driver circuit. Figure 7 and 8 shows the XY stage interfacing with PC.

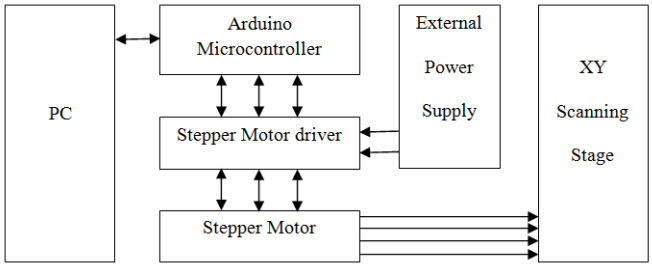


Fig.5 Block diagram of computer interfacing of XY Scanning Stage

VII. CONCLUSION

In this study, we have designed and fabricated the XY scanning stage which is driven by stepper motor and controlled by Arduino microcontroller. Also we have proposed the control mechanism for the stage motion in XY plane. Using Arduino board and easy driver circuit we can control and interface the XY Stage with computer. This work is beneficial in precision engineering such as in 3D printers.

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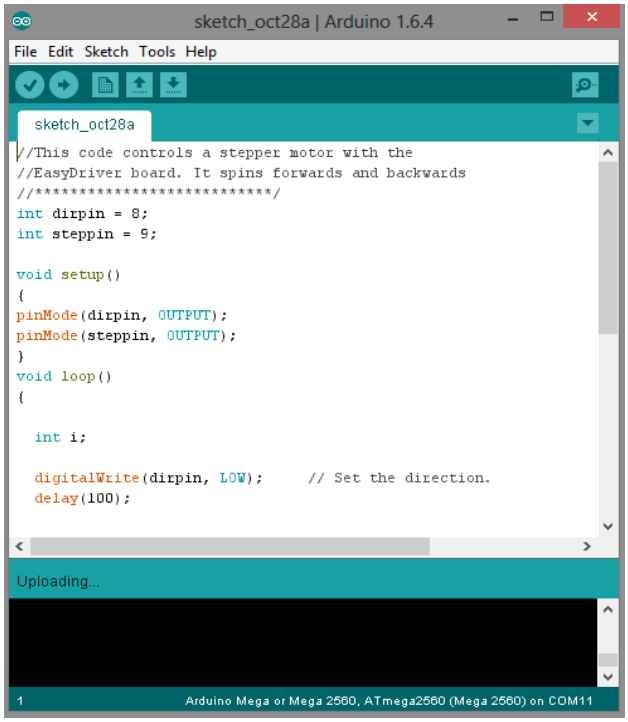

Fig.6 The program uploaded to the Arduino software

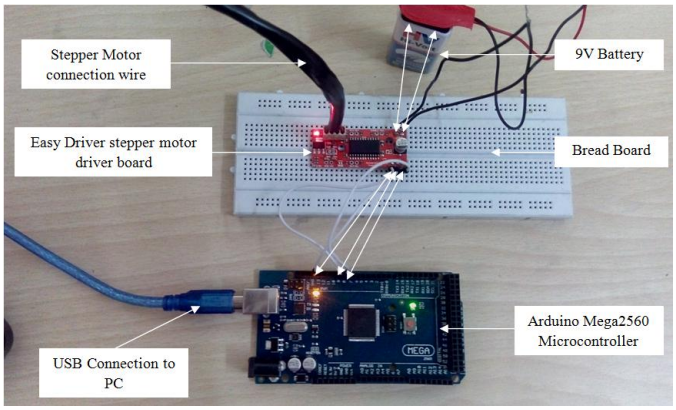

Fig.7 Wire connections for system interfacing

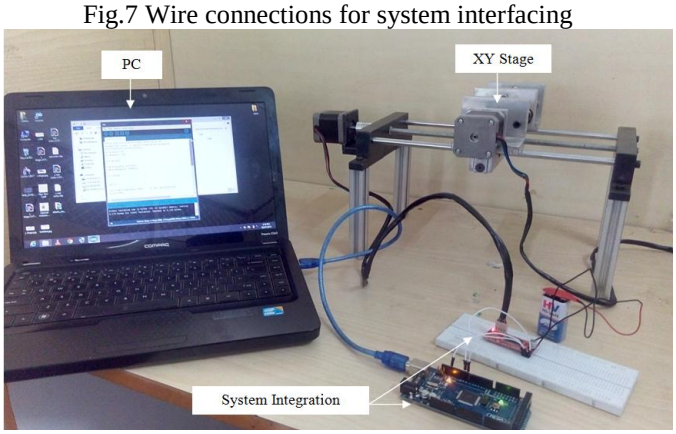

Fig.8 The XY stage interfaced with PC

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