



Design and implementation of a three axis digitally controlled traverse system for flow surveys in a drying chamber

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Abstract

The current paper describes the design and development of a pc-controlled three axis traverse system that aims to serve extensive velocity and temperature measurements into the drying chamber of a laboratory scale convective dryer. The traversing gear design has been conducted based on the convective dryer's specific experimental requirements and limitations. The fabricated traversing gear uses a trapezoidal lead screw-nut assembly supported by linear ball bearings, coupled with bipolar stepper motors for positioning in three dimensional spaces. A custom drive system solution was selected for achieving accurate motor control, paired with computer software developed using the LabVIEW[®] graphical programming environment. The functionality of the traversing system was experimentally verified by testing mechanical and electronic assemblies, but also by determining the per axis positioning error.

Keywords: Fluid Flow Measurement, Digital Control, Motion Control, Displacement Control, Electromechanical Devices.

1. Introduction

An x - y - z traverse mechanism, which is composed of a motion mechanism driven by linear actuators, is a crucial component of an instrumentation system used in experimental fluid dynamics. Velocity and temperature measurements in flowing media involve the need of traversing a probe at a designated position with certain accuracy [1] [2] [3] [4]. As a result such a traverse system is a convenient and accurate way of acquiring multiple measurements at multiple locations. Traverse mechanisms either mechanical or electromechanical have been extensively used in wind tunnels for velocity profile measurements, with the simplest implementation being that of a Cartesian robot [5] [6]. Cartesian robots have their axes arranged according to the Cartesian coordinate system which results in a cubic working volume appropriate for rectangular cross-section test cells.

Although there are commercial products available, appropriate for accomplishing multipoint measurements, possible modifications and tuning is inapplicable or it can be only performed by the manufacturer. In addition, performing multipoint measurements manually is a tedious task for the researcher and introduces various sources of errors. This leads to the development of a traverse system suitable for multipoint measurements, taking into consideration existing designs and adapting certain features. Thus, this paper reports the development of an integrated traverse system designed for a specific experimental facility. The proposed traverse system is to be designed according to the Cartesian principle in order to be installed on laboratory scale convective dryer featuring a rectangular drying chamber [7]. Due to space related restrictions, the mechanical and electrical components have to be minimized. In addition, cable length, connecting the traversing gear with the control unit is also kept at a minimum. A virtual instrument using National Instruments (NI) LabVIEW[®] [8] is developed featuring a graphical user interface to aid the navigation of the traverse gear.

2. Design requirements and specifications

Tzempelikos et al. [7] designed constructed and evaluated a new laboratory convective dryer, in which the traverse gear is going to be utilized. Intensive study has been done in order to determine the design requirements and specifications based on technical drawings of the drying chamber and predefined experimental parameters. By analyzing those factors the following requirements were introduced:

- It must be installed inside the air duct at the downstream end of the drying chamber in order to reduce complexity and possible air leaks introduced from poor air sealing.
- It must be able to operate under ambient conditions of up to 60°C and 20% of relative humidity.
- Components dimensions must be kept at a minimum in order to reduce interference with the airflow.
- It must be able to be removed from the main structure easily and without damage to the structure or the device itself.
- It must be able to be controlled remotely using a PC through USB connectivity and be positioned without direct line of sight.
- The working volume must be at least 20% of the net drying chamber volume which is found to be 0.081 m³.
- It must be able to achieve position error less than ± 0.1 mm

The proposed traversing device will act as a measuring device for future velocity measurements and as a result the final prototype should be in accordance with the above specifications due to the fact that those are closely connected to the measuring chamber's properties.

3. Mechanism

The traverse gear model and fabricated prototype installed in the drying chamber is shown in Fig 1. It is mounted on the vertical axis of the installation and on top of the measuring chamber for added structural support and enhanced working space. In addition by mounting the mechanism onto a removable corner duct the whole system can be removed from the installation without disassembling any traversing gear component. Linear motion is achieved by linear floating bearings with recirculating ball channels running on steel shafts ensuring smooth operation and low friction coefficient resulting in reduced wear and reduced power requirements. Trapezoidal lead screws coupled with appropriate stepper motors have been selected for providing backward and forward motion for each direction. A custom drive system solution has been developed in order to achieve motor control through a personal computer with USB connectivity by employing an external signal generator and a standard stepper motor driver.

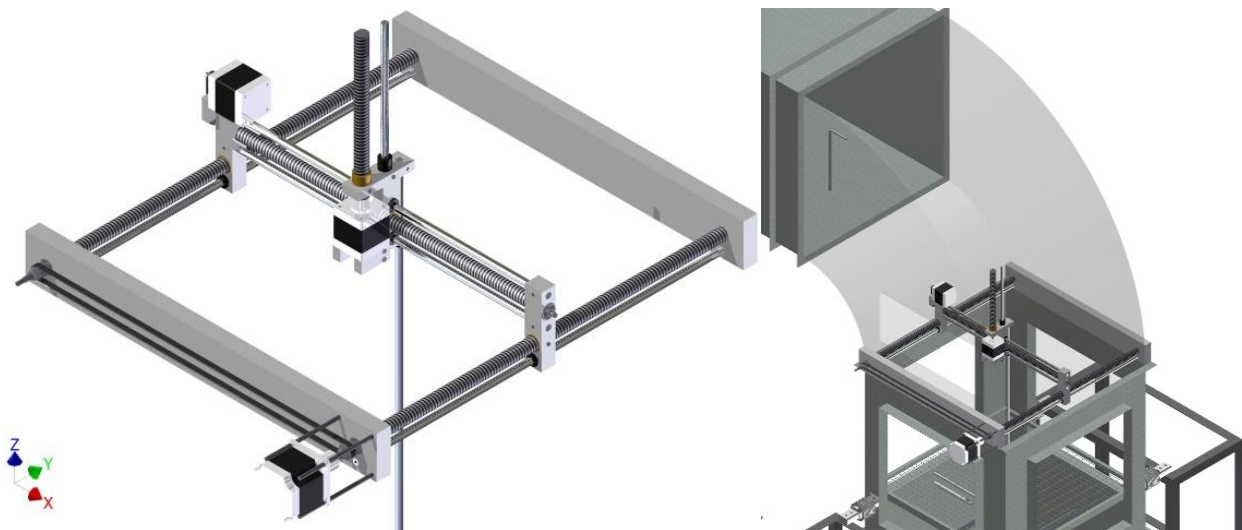


Fig. 1: Traverse Gear CAD Model and Its Mounting Position Downstream of the Drying Chamber.

Manufactured components located inside the drying chamber cover a total surface area of 0.0249 m² which is 9.96 % of the total surface area of the rectangular section measuring 0.5 by 0.5 meters. Thus, the traversing gear does not create a serious void in the airflow which in other case would have been problematic. Traversing distance in X, Y and Z axis are 303 mm, 416 mm 165 mm respectively defining a working volume of 0.021 m³ which is 26 % of the net drying chamber volume. The net volume was found to be 0.081 m³. Measurements will be taken in close proximity to a tray located inside the chamber, which is the reference plane and as a result the Z axis range is well suited for this application. However, the Z axis maximum and minimum distance can be manually set thus changing the working volume offset from the reference plane.

3.1. Materials

Aluminum is one of the most versatile engineering metals used in a variety of applications due to the fact that it offers a wide range of properties. The properties that make aluminum suitable for engineering application is its low density yielding a low weight product, its good strength-to-weight ratio and its excellent machinability and corrosion resistance. Aluminum alloys such as 2024, 6000 and 7000 series offer increased strength than pure aluminum and are extensively used in demanding applications [9]. For the current application the aluminum alloy 6063-O was selected to be the main fabrication material. Due to the fact that it belongs in the 6000 series alloys, it offers increased strength and corrosion resistance but also is a lower cost replacement of the higher cost 7000 series alloys.

Apart from aluminum, surface-hardened steel is used for the trapezoidal lead screws, brass for the lead screw nuts for reduced friction coefficient and high alloy steel for the guide shafts with a mirror finish. As far as cabling is concerned, standard silicone coated wires and shielded coaxial cables exclusively for sensor interfacing were used.

3.2. Drive system

The most important part of a traverse device is the selection of a suitable drive system as it has a direct impact on the power requirements, controlling electronics and achieved accuracy. The drive system consists of a mechanical system that can provide linear motion, an appropriate electric motor for providing the required torque and of an electronic control system responsible for accurate motor control.

Mechanical motion is achieved by sliding the assembly on 8 mm diameter hardened steel shafts with the aid of linear ball bearings. Linear bearings are extensively used in relevant applications as they offer reduced friction and motion resistance with substantially lower cost than linear guide rails. In addition continuous lubricant feed is not required due to the fact that load forces and speed requirements are minimal. For each axis two sets of linear bearing/shaft are used in order to increase stiffness and cancel any unwanted degrees of freedom. The sliding assembly is coupled with a trapezoidal lead screw-nut assembly which is responsible for providing forward and backward motion. A TR16-4D screw is selected measuring 16 mm in diameter with 4 mm lead. Although a 16 mm screw features high capacity force loading, in this particular application serves as a stiffening component. Each screw is connected to a stepper motor which provides the required torque for overcoming friction forces and setting each different axis in motion. However, force loading in each direction is different due to the fact that traversing masses and friction forces are different. The same general power screw principle is applied for each axis and as a result the torque required to overcome screw-nut friction and applied loads is calculated according to the following equation [10]:

$$T_R = \frac{Fd_m}{2} \left(\frac{1 + \pi f d_m \sec a}{\pi d_m - fl \sec a} \right) (Nm) \quad (1)$$

Where

F is the force loading on the screw which is opposite to the direction of movement,

d_m is the mean diameter of the screw,

f is the friction coefficient between screw and nut,

l is the screw lead and

a is the thread angle of the screw.

Based on the minimum torque requirements the stepper motors are selected. For the X and the Z axes, two 35BYG304 NEMA 14 stepper motors were selected, delivering 122.5 mNm at 1A/phase. For the Y axis, a KH56KM NEMA 23 stepper motor was selected, delivering 932 mNm at 2A/phase. The rated torque that the three motors provide is more than sufficient; however, the higher torque capacity results in flexibility when choosing maximum speed and acceleration parameters and their dimensions were favorable regarding the X and Z motors. The Y axis lead screws are synchronized together by a timing belt and the stepper motor is directly coupled to one of them using an aluminum flexible coupling. The X axis lead screw is connected to the stepper motor with a timing belt due to space constrictions and the Z axis lead screw is directly connected to the motor without a flexible coupling. The summary of the technical specifications of the traverse gear is shown in Table 1.

Table 1: Summary of the Technical Specifications

Description	Specifications		
Materials	Lead screw: TR16-4D Steel	Lead screw nut: Brass	Sliding rail: Alloy Steel
Minimum torque	X axis: 31.84 mNm	Y axis: 5.36 mNm	Z axis: 11.82 mNm
Motors	X axis: 35BYG304 122.5 mNm	Y axis: KH56KM 932.0 mNm	Z axis: 35BYG304 122.5 mNm

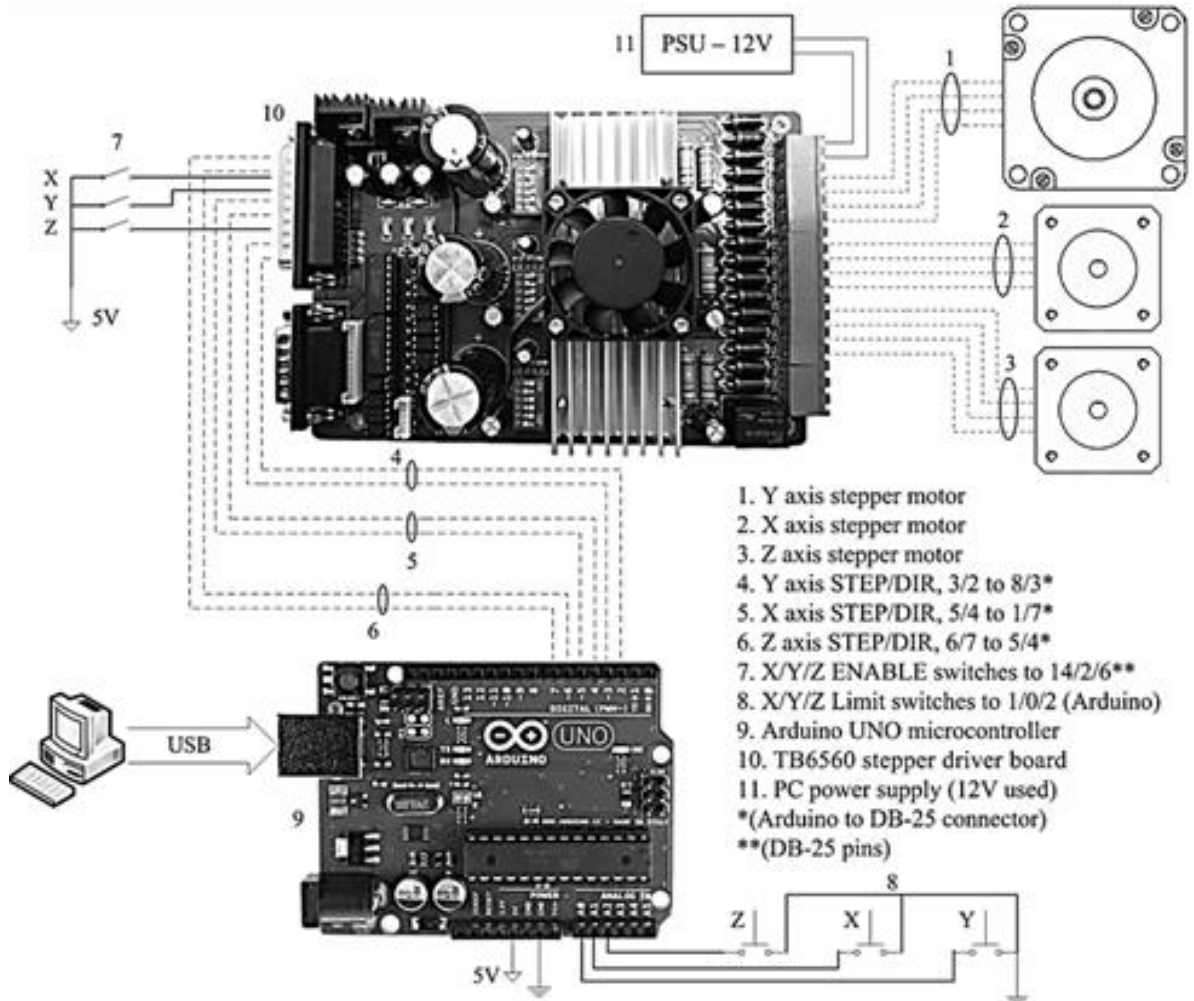


Fig. 2: Motion Controller Wiring Diagram.

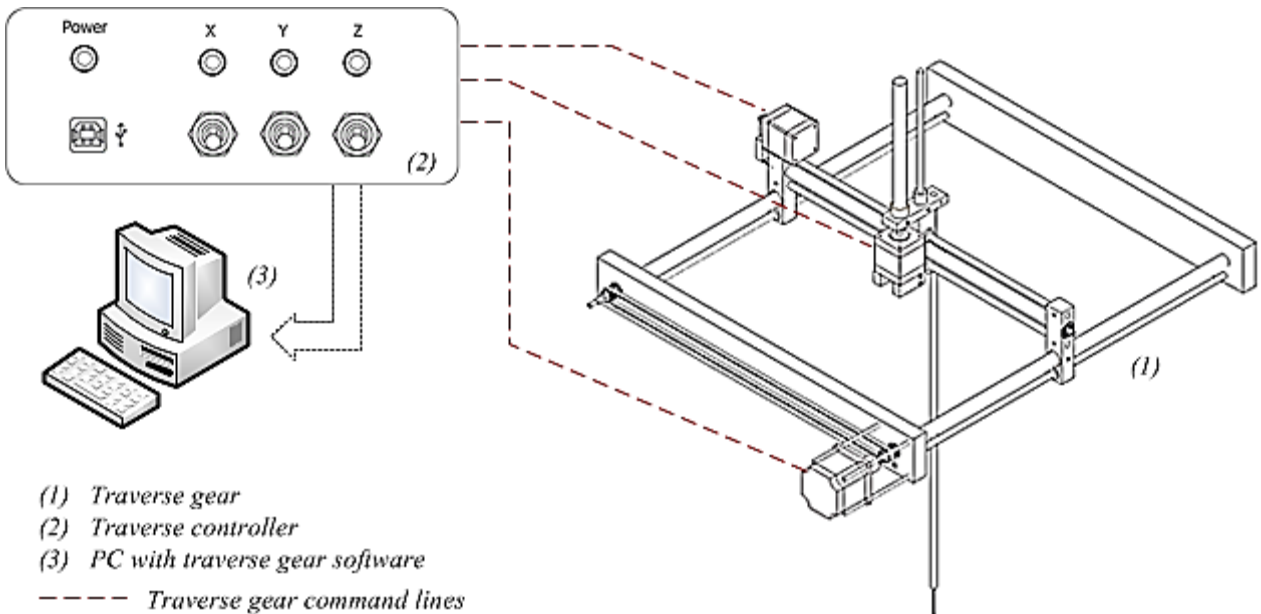


Fig. 3: Schematic Drawing of the Three Axis Traverse System.

Controlling the motors requires a stepper motor driver capable of delivering high power to the stepper motors and a PC interface for software integration. Thus a bipolar stepper motor driver was selected with a maximum rating of 3 A/motor. Motors are connected to the driver board via a connector box for quick disconnect. In order to achieve precise motion control an external signal generator is proposed to be used instead of using a PC's parallel port which is outdated. Power to the stepper driver and subsequently to the motors is provided by a computer power supply at a

maximum current of 10A at 12V. An Arduino® microcontroller [11] was utilized for this task providing USB connectivity to a host computer (Fig. 2). The microcontroller uses an open source firmware developed for NI LabVIEW® [8] thus interfacing with a custom application developed using LabVIEW® programming environment is straightforward. An extra addition to the system is a USB camera facing the upstream side of the measuring chamber allowing control of the traversing gear without direct line of site. A schematic drawing of the custom made three axis traverse system is shown in Fig. 3.

3.3. Software implementation

Interfacing with the stepper motors is achieved by a PC application developed using NI LabVIEW® and a set of special VIs for the Arduino® microcontroller belonging in the LabVIEW® interface for Arduino® library [8] [11]. The developed software allows full control of the traversing gear assisted by a USB camera in order to avoid collision with objects inside the work volume. Connection of the motion controller with the PC is achieved via a USB cable; however the USB port is emulated as a serial one operating at a baud rate of 115200 bps. The main purpose of the software is to read the user's inputs, which essentially are what distance its axis will traverse at a certain speed and acceleration, returning the incremental and cumulative traversed distance for each axis along with the visual feed of the drying chamber.

In Fig. 4, the flowchart of the developed traverse system software is shown. To ensure that stepper motors are instructed to move exactly as intended to, for each direction and axis an event is assigned. Thus the software waits for an event to occur and then sends data to the driver controller and subsequently to the motors. Traversed distance is always stored into arrays for each direction in order to keep track of the cumulative distance travelled. A "zero" function is also available in order to set different origin points. The functionality of the software is supported by an intuitive user interface which is not confusing and complex, avoiding navigation errors. Each traversing direction is represented by a button with a plus or minus sign and an arrow indicating the actual moving direction. Finally, speed, acceleration and signal connections assignments for each axis are available to the user through a settings tab.

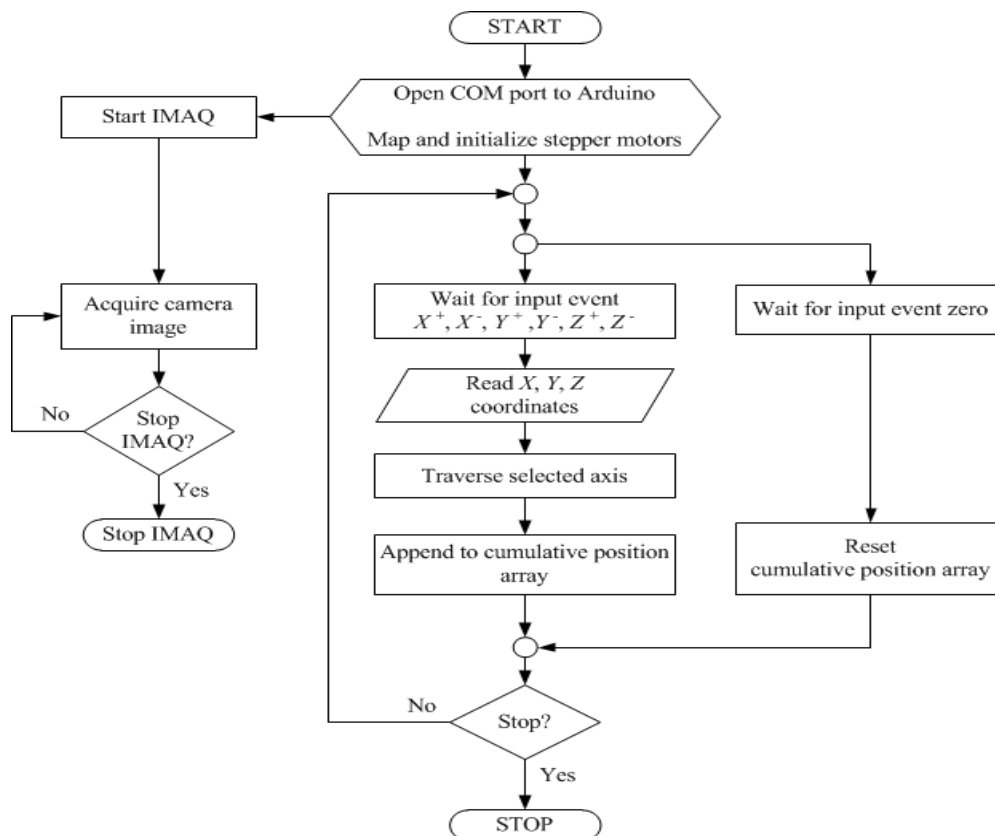


Fig. 4: Traverse System Software Flowchart.

4. Configuration testing

Several tests have been conducted in order to validate the functionality of the traverse gear prototype. Three tests were conducted, testing for operation under temperature cycling, motor controller and software function and positioning accuracy on each axis.

4.1. Temperature cycling

Internal components of the traversing gear were exposed to temperatures ranging from 40 to 60°C, air velocities from 1 to 3 m/s and relative humidity from 5 to 20 % RH. Exposure time was over 100 hours due to the nature of the drying experiments conducted inside the drying chamber [12] [13]. During exposure time all axes were traversed for a brief distance in order to check for normal operation. At the end of the drying experiments the traversing gear performed without any degradation of internal components and a close inspection verified that all electronic gear were intact and fully operational.

4.2. Motor controller and software function

The electronics components and developed software were verified through configuration testing. The electronic drive unit performed as expected without exciding the maximum amperage rating of the power supply and no overheating of the boards and cables was observed. In addition, the available firmware version for the microcontroller was stable without crashing or producing false signals.

The developed software was able to successfully move each axis to the desired position while continuously keeping track of the cumulative distance traveled as well as displaying a video feed of the measuring chamber. The software was tested on both single and dual core Intel® platforms without impairing functionality and execution speed.

4.3. Positioning accuracy

Before assembling the traversing gear components, each part was verified dimensionally with an electronic caliper accurate to ± 0.02 mm and a micrometer accurate to ± 0.01 mm where it was applicable. The traversing system was installed on the measuring chamber where positioning accuracy per axis was evaluated. Positioning accuracy testing for each axis was performed using a calibrated dial indicator accurate to 0.01 mm and a resolution of 0.005 mm. A magnetic platform was utilized for fixing the dial indicator on a secure location. During the measurements temperature and relative humidity were constant at 19°C and 30 % RH respectively.

Each axis was traversed for a known amount of distance based on a calibration applied to translate steps to actual distance. For the Y and Z axis the selected distance is multiplied by a factor of 100 yielding a resolution of 0.01 mm/step. For the X axis the factor is 200 resulting to a resolution of 0.005 mm/step. The test increment for X and Y axis was 1mm and for the Z axis was 0.1 mm. The maximum range of the dial indicator is 10 mm thus data points were gathered both from backward and forward motion. The results are shown in Fig. 5.

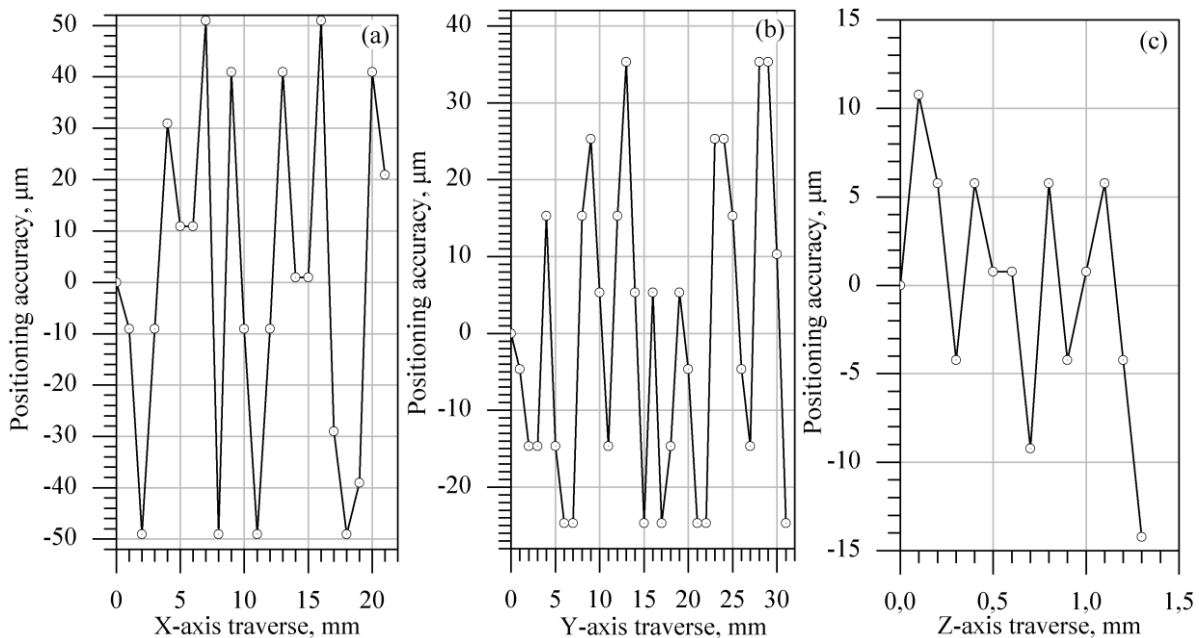


Fig. 5: Position Accuracy for the Three Linear Axes.

Table 2: Positioning Performance Results

Axis	Resolution (µm)	Error (µm)
X	5	± 34.8
Y	10	± 20.4
Z	10	±7.0

Measurement points are created by subtracting the value visible on the dial indicator from the desired value sent by the software, i.e.

$$\Delta x_1 = x_{exp} - x_{actual} \quad (2)$$

Each graph represents the difference of each measurement point from the mean value, versus the desired distance, i.e.

$$\Delta x_2 = x_{exp} - \bar{x} \quad (3)$$

The standard deviation for each data set is calculated according to the following equation:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}} \quad (4)$$

Where

σ (μm) is the standard deviation,

x_i (μm) is a data point and

\bar{x} (μm) denotes the mean value of the data set.

In Fig. 5a, the X axis performance is shown. Values are ranging from 50 to -50 microns with a standard deviation of 34.8 microns. In Fig. 5b, the standard deviation of the measurements was found to be at 20.4 microns with a data range of 60 microns. In both X and Y axis, the range fluctuation is associated with the screw lead error due to the fact that common trapezoidal lead screws does not offer the best results in positioning equipment in contrast to ball screws, a more expensive but accurate positioning screw. However, the Z axis performs with a standard deviation of 7 microns and a range of 25 microns (Fig. 5c). This is feasible partly because the travel length is shorter and partly because the weight of the Z axis components acts as a preload on the screw providing continuous pressure on the nut. A summary of the results is shown in Table 2.

5. Conclusion

A working three axis traverse gear prototype was designed, fabricated and tested for operation. Extensive tests were conducted to validate that the fabricated traversing gear was in agreement with the design requirements. It was observed that mechanical hardware, electronics and software performed without issues and that the design criteria were met, especially those regarding position error, working space and maximum temperature and humidity ratings.

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