Project work on

Motorised 1D linear Stage Design

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Declaration

I hereby declare that the work presented in the report entitled **Linear motorized stage**, has been submitted by me in fulfilment of the requirement of the award of the Degree of the **Bachelor of Technology in the Department of Physics, Indian Institute of Technology, Roorkee**. I also declare that the I have been working since **August 2022** under the supervision and guidance of **Prof. Monojit Bag, Department of Physics, Indian Institute of Technology Roorkee**. The matter presented in the report has not been submitted for the award of any other degree of the Institute or any other Institutes.

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I would like to thanks Tinkering Labs of IIT Roorkee, for providing me access to 3D printers and power tools, without which this project wouldn't have been possible

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Place: Roorkee

Date: May 2023

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ABSTRACT

The main objective of this project is to make a working model of a motorized linear stage. Linear stages in the market are too expensive (a 1D stage would cost around five lakhs INR). My aim is to make a linear motorized stage at a low cost, which can be programmed and whose design can be customized so that we can use it in many applications.

All starts with understanding the basic mechanics of platform movement, motor, coupler, and lead screws. After this, I learned about all the electronic components required to make this instrument, like the stepper motor driver, keypad, LCD, I2C, and their interfacing with the Arduino development board. Modular code for each component was written and tested.

After understanding the required mechanics and electronics, I had to make the stage's design based on our lab's experimental requirements. Then making a 3D model of this design in Tinkercad software. 3D printing that design and assembling it on a platform. Making the circuit module-wise such that testing and debugging would be easier, connecting all modules and testing the functioning of the whole circuit.

Changing the design again, according to new experiment requirements. Writing new code according to the requirement of the experiment. Uploading code and using the instrument.

This cycle will continue according to the new requirement. Thus finally, I made a low-cost programmable customizable linear motorized stage.

Chapter-1
INTRODUCTION

1.1 About linear stage.

A linear stage is a precise positioning device that can be operated manually or motorized. It is typically available as a single axis, an XY stage, or an XYX translation stage.

It consists of a base on which there is a moving platform joined by some form of guide or linear bearing so that the platform is restricted to linear motion with respect to the base. The actuator is there to move the platform.

Drive options (actuator)

Drive options for manual linear stages include a micrometer head (springs are for continuous attachment) or adjustment screw. For the motorized stage, the drive is given by a stepper or servo motor

Fig.1.1 – Manual linear stage

Fig.1.2 – Motorized linear stage

Platform type:

The platform can be a dovetail slide, ball-bearing slide, or roller slide. The dovetail slide is the most often used and economically advantageous stage with the highest load and most extended travel range.

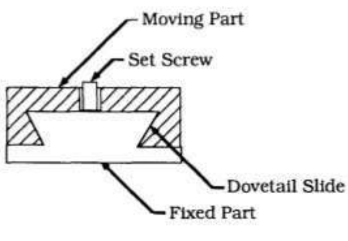

Fig.1.3 – Dovetail slide platform

Fig.1.4 – Ball bearing slide

Pros and cons of manual linear stage:

They are the most straightforward and economical. With micrometer heads, position resolutions of 1 um are feasible. Human error cannot be eliminated; it will always exist. Motorized stages are therefore preferable for high-load/high-speed applications and for situations where manual adjustment may be challenging.

1.2 Applications of linear stage

A linear stage can be used in photonics (for lens/fiber alignment), semiconductor manufacturing (quality control of wafers during inspection procedures), under a microscope (for moving the sample and examining it), and in various experiments where high accuracy in position control is required.

Here I have used the linear stage in bending and stretching a thin perovskite supercapacitor to know how their properties change. I have used the stage in bending stretching of thin films to observe their properties.

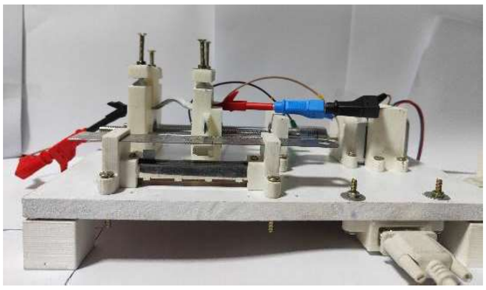

Fig.1.5 – experiment using stage

Fig.1.6 – Stage under microscope

Chapter-2
MOTORIZED 1D LINEAR STAGE

A motor drives these stages to provide the desired point to point translation. A controller is required to control the motion of the stage.

2.1 Components of motorized stage design

a) Motors

Two main motors used in motorized stages are stepper motors and servo motors. They are available in a variety of sizes of different torque-speed profiles. Factors to consider while choosing a motor is torque and speed requirement, carrier load, positional accuracy, and operating environment.

Servo motor

A Servo motor is a rotary actuator that consists of an AC / DC motor, a sensor, and a control circuit, all in a single enclosure. The control circuit compares the feedback from the sensor to a reference input signal and gives output voltage to the motor so that sensor output and reference are the same.

Thus because of this servo mechanism, we get great precision, and due to the gear system, we get high torque.

To control the servo motor, we have to provide a PWM signal (control signal) to the control circuit from a microcontroller. The control signal should have a frequency of 50 Hz. The pulse width determines the servo's angular position. Since they are physically limited in their range of motion, some servos typically spin 180 degrees

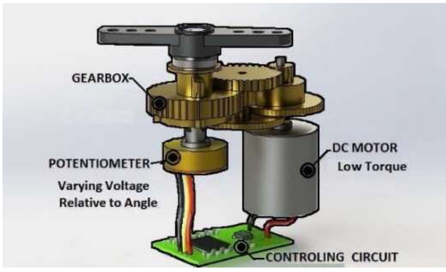

Fig.2.1 – Servo motor internal

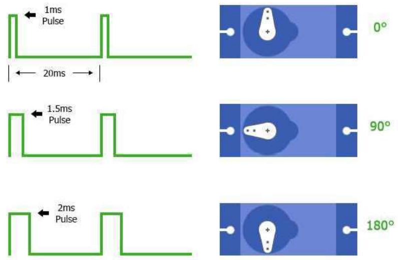

Fig.2.2 – Servo motor control

Stepper motor

A Stepper motor is a brushless DC electric motor that moves in discrete steps. They have several coils that are arranged into "phases." The motor will rotate one step by sequentially energizing each phase, one at a time. The motor can be controlled in an open-loop system as long as the motor is correctly sized to the application with respect to torque and speed.

To control the stepper motor, all we have to do is to energize each phase in sequence. Driver circuits like A4988 and DRV8825 are used to control these motors. These driver circuits provide the required current to each coil at the right time. Driver circuits are controlled via a microcontroller, which makes operating the stepper motor much easier.

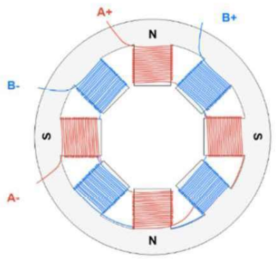

Fig.2.3 – Stepper motor internal

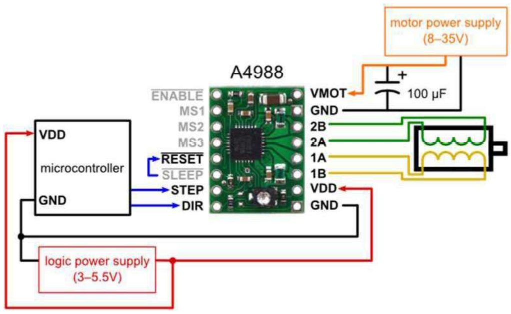

Fig.2.4 – Stepper motor control

Comparing both motors

Due to their high pole count, stepper motors offer precision drive control for motion control applications. They are reasonably priced and offer much torque at low speeds. They lose almost all of their torque at high speeds. They generate a lot of heat and vibrations and are prone to resonance problems.

Servo motors provide high levels of torque at high speeds. They work with an efficiency of between 80 and 90%. Servo motors can run on an AC or DC drive without resonance and vibration problems. They are more expensive than stepper motors, which is a major disadvantage.

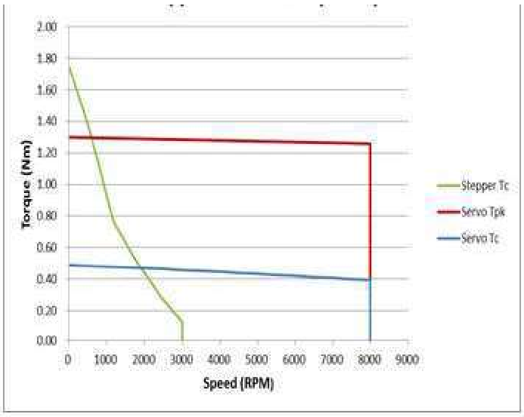

Fig.2.5 – Torque vs speed of stepper and servo motor.

b) Feedback devices

These devices are sensor that reads information regarding the motor's speed and position and sends it to the controller as a feedback signal. Some of these sensors are encoders and switches. We can use a slide potentiometer for distance measurement, and for angle measurement, we can use a Hall Effect angle measurement sensor

c) Controller

It controls the whole process i.e. takes input from user (can be a software / hardware) command and convert it into control signals for motor drivers. It also takes feedback signals typically from a servo motor, and/or from the mechanical stage for position awareness and corrects for any errors in intended motion.

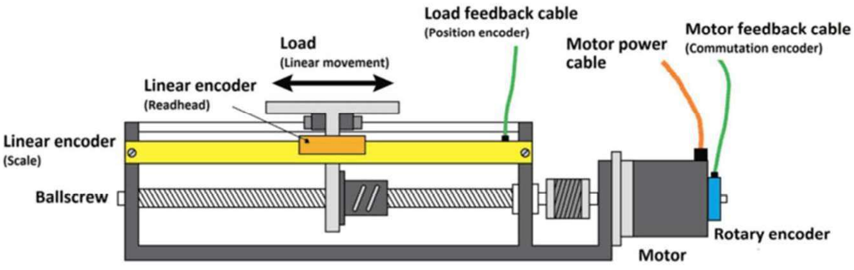

Fig.2.6 – Controller.

d) Lead screw and ball screw

These are mechanical linear actuator that translates rotational motion to linear motion. Lead screws use threaded metal bars and a threaded nut in direct contact with the screw, i.e., sliding friction is there. A ball screw consists of a screw shaft and a nut containing balls that roll between their matching helical grooves, i.e., rolling friction is there. Ball screw is better, but they are costly.

Fig.2.7 – Lead screw

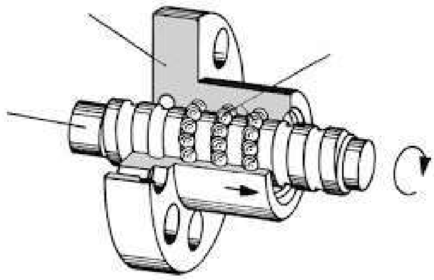

Fig.2.8 – Ball screw.

e) Main stage

As discussed, the main stage can be of three types, dovetail slide, ball bearing slide, or roller slide. Dovetail is mostly used.

f) Coupler to align motor and lead screw

Couplers are typically used to join two spinning pieces of equipment while allowing for some end movement, misalignment, or both.

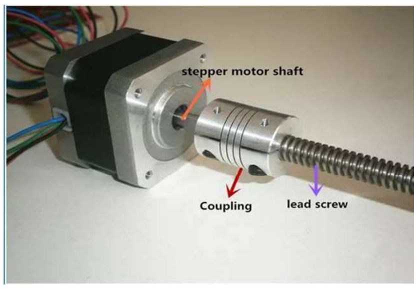

Fig.2.9 – coupler

2.2 Linear 1D stage of Thorlabs

Thorlabs is a leading company in manufacturing these stages. They provide stages of high-specification and quality products. According to Thorlabs website, the cost of below mentioned 1d linear stage is $2643, and we have to buy a controller to control the stage, and the controller costs $1607. Therefore the total cost is $4250 = 3, 40,000 INR.

We can see that these stages are costly; thus, a low-cost stage with certain specifications is required.

Fig.2.10 – Thorlabs 1d stage

Key Specifications[a]	
Travel Range	150 mm (5.9")
Velocity (Max)[b]	30 mm/s
Minimum Achievable Incremental Movement	0.1 µm
On-Axis Accuracy[c]	2.0 µm (Typical) 5.0 µm (Max)
Bidirectional Repeatability[d]	1 µm
Backlash[e]	<3 µm
Horizontal Load Capacity (Max)	20 kg (44 lbs)
Vertical Load Capacity (Max)	5 kg (11 lbs)
Actuator Type	Stepper Motor
Cable Length	3.0 m (9.8 ft)
Recommended Controller	Benchtop Stepper Motor Controllers

Table1 – Thorlabs stage specifications

Chapter-3
MAKING 1D LINEAR MOTORISED STAGE

Our main focus is to make a 1d stage affordable, as market stages are expensive.

3.1 Fixing our requirements

The speed range of stages available in the market varies from 1mm/s to 100mm/s. . . Staying in the lower range, this stage will have a speed of 10-30 mm/s. Considering cost and degree of accuracy, I have chosen lead screws (square tooth as their efficiency is high). Lead is 2 mm, and the diameter is 8 mm. As servo motors are required for costly and high-end stages, thus we are using stepper motor. The load capacity would be 10 Kg in the horizontal direction.

Considering the speed and torque requirement, I have chosen NEMA 17, 6.5 Ncm stepper motor: (12 - 24) V, four leads, 1.2 A/phase, and 1.8-degree step angle.

Our motor's current rating is 1.2 A/phase, so we have to use a driver circuit that can provide this current. Such a driver is DRV8825.

Motor driver:	DRV8835
Motor channels:	2
Minimum operating voltage:	0 V
Maximum operating voltage:	11 V
Continuous output current per channel:	1.2 A[2]
Peak output current per channel:	1.5 A
Continuous paralleled output current:	2.4 A[2]
Maximum PWM frequency:	250 kHz
Minimum logic voltage:	2 V
Maximum logic voltage:	7 V
Reverse voltage protection?:	Y

Fig.3.1 – DRV8825 driver

3.2 Making 3D model of stage

The 3D model is made using Tinkercad software. The components shown in the 3d model are Stepper Motor (NEMA 17 6.5 kg-cm), a lead screw (2mm pitch), Mechanical Coupler, a Rotary and linear and rotary encoder (not discussed now), a linear scale, and 3D printed structure.

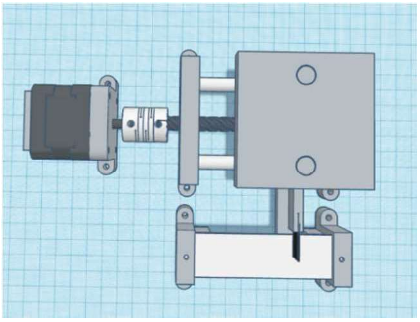

Fig.3.2 – 3D model of stage (top view)

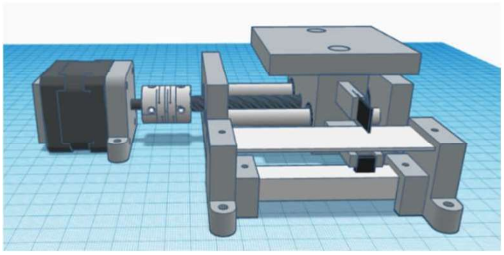

Fig.3.3 – 3D model of stage (side view)

3.3 Characterization of stage

Travel Range	6 cm
Linear resolution	5 um
Modes of operation	4 (low vibration mode)
Input device	Keypad
Output device	LCD (20x4)
Motor used	NEMA 17 6.5 kg cm
Driver used	A4988
Controlled used	Arduino UNO

Table 2 – Stage characterization

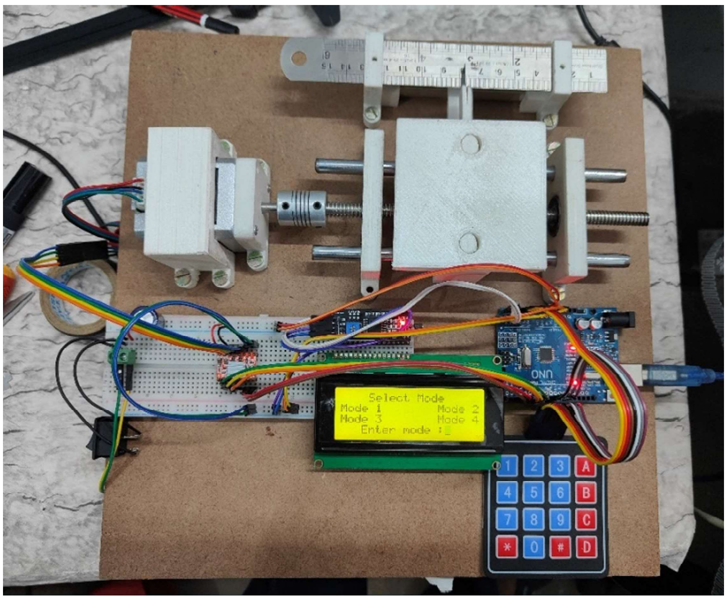

Fig.3.4 – Working model of stage

3.4 Problems with the stage

In this project, three major problems with the stage are vibration, accuracy error, and calibration. Below are discussed sources and solutions for each problem.

a) Vibration

When a stepper motor makes a step, the system's inertia causes the motor to slightly overshoot (or undershoot) the intended step angle. The motor then oscillates until it finally settles at the commanded position.

Vibrations can be of three primary types: Step movement is the cause of low-speed vibration (about 0–50 RPM). Torque variation or resonant frequency are the main causes of mid-speed vibration (about 50–200 RPM). Back EMF and instability of constant current control cause high-speed vibration (about 500 RPM and above).

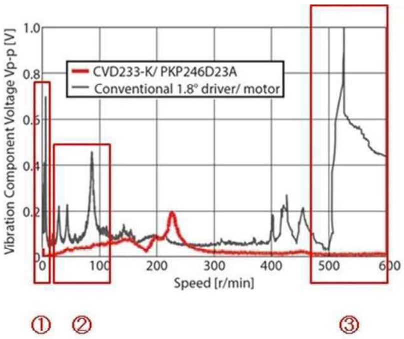

Fig.3.5 – Vibration vs speed

Mechanical methods to reduce vibrations

At the base level, we are increasing system inertia to reduce vibration. 1) Adding a mechanical damper between the motor and the load. It adds extra inertia to the shaft, helps to absorb the vibration, and provides a stable damping effect. 2) Adding a gearbox to the system. Increases in rigidity can help suppress vibration transmission from motor to load, and gear friction can help reduce overshooting and undershooting. 3) Avoiding motion at or close resonant frequencies. The easiest way to avoid resonance could be simply changing the operation speed, so the motor will not hit its resonance point.

Fig.3.6 – Motor with damper

Fig.3.7 – Gearbox + Motor

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Electrical methods to reduce vibrations

At the base level, we reduce the energy sent to the coils.1) The oscillation is reduced by micro-stepping at smaller step sizes. By giving the coils less excitation energy, it smooths out the stator flux. Less noise and vibration are produced as a result. It also increases stepper motor position accuracy. 2) Reducing current to reduce torque stiffness. With less current input, the motor will generate less torque. Less energy will be required to rotate the rotor as a result, which will reduce vibrations.

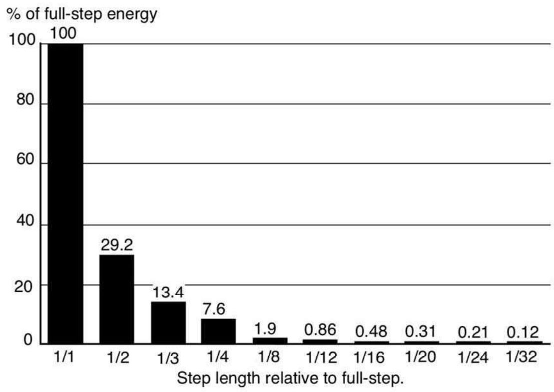

Fig.3.8 – Vibration energy with step length

Here I have chosen the second electrical method, i.e., micro-stepping, as it adds no extra cost. In this mode, the motor runs in the following two modes. 1) Full-step mode: 200 steps are involved for one complete revolution. (High vibrations). 2) 1/16 micro-stepping: for one complete revolution there are 16x200 = 3200 steps involved. (Low vibrations).

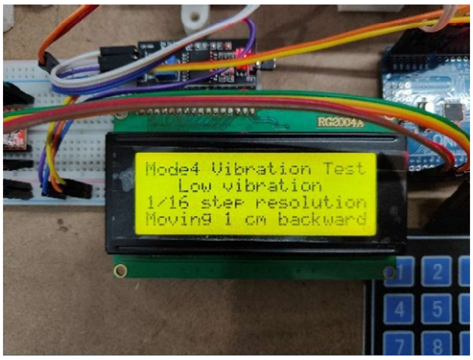

Fig.3.9 – Low vibration mode 1

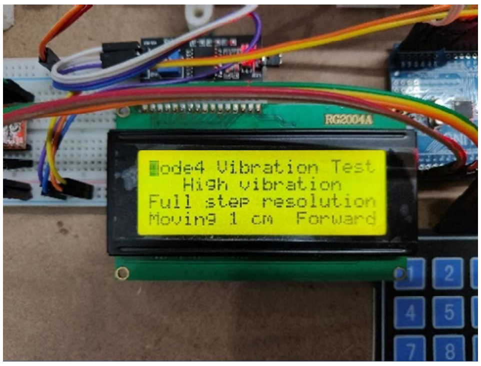

Fig.3.10 – Low vibration mode 2

b) Accuracy error and calibration

Rotational accuracy error

While giving pulses to the motor, some pulses might be missed. In order to measure this rotational error, a small experimental setup is made.

In this setup, an arrow is attached to the motor shaft, which moves above a circular disk. Each division of the circular disk is 1.8 degrees, i.e., 200 divisions. The motor runs for some complete rotation and is visually checked whether it returned to its original position. The motor is rotated in full step mode, i.e., 1.8 degrees per step. For n complete rotation, 200xn steps are required

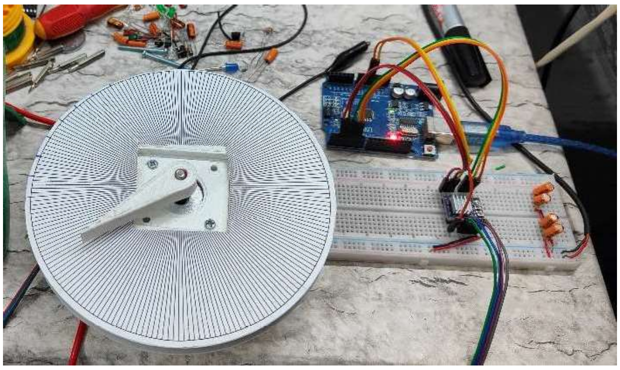

Fig.3.11 – Angular error setup

Error conclusion: There is no loss in steps due to pulse miss. However, there may be some manual errors since this experiment is done manually. A high-precision rotary encoder is required to go for a more detailed examination.

Linear accuracy error

Since there is no error in rotary motion, there should be no error in linear motion also by theory. In linear motion, an error occurs due to the following reasons: calibration error, initial power-on error, driver error while inputs are given, and stall error due to load.

In the experimental setup, to and fro motion is done using the 1D stage. The indicator is set at 6cm; then it goes to 7 cm, then back to 6cm, repeating the same motion for n times in full step mode. Therefore for one completion traversal (6cm to again 6cm), the distance traveled is 2 cm. Steps moved = 2000 steps, for n such traversal steps = 2000xn.

Fig.3.12 – Linear Error 1

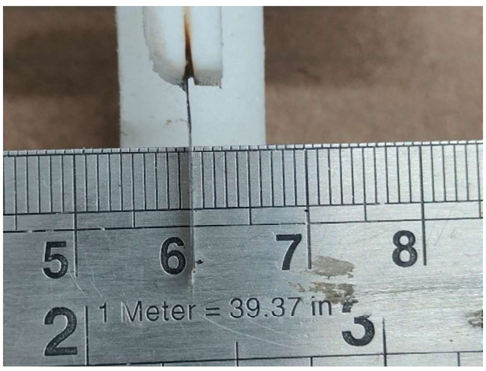

Fig.3.13 – Linear Error 2

Errors conclusion: Initial power on error is three steps on average. While we take input from the keypad, the driver is not set; therefore, it gives some random pulses. These can be corrected by moving the lead screw. Once the stepper motor starts after these calibrations, there is no step loss, as observed manually

3.5 Flow of code and final circuit

The code flow is: 1) Print options on LCD. 2) Take input from the keypad. 3) Choose the mode accordingly. 4) Print options to enter values. 5) Take values from the keypad, convert those values to steps, and instruct the driver to move the motor. 6) Repeat.

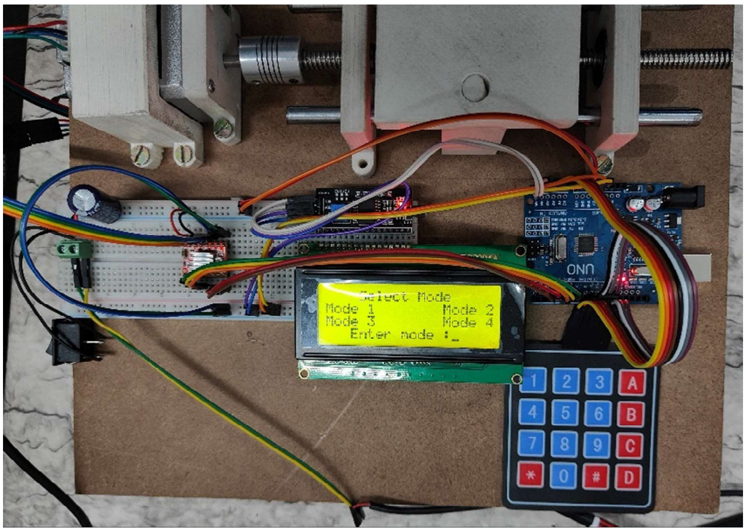

Fig.3.14 – Circuit of stage controller

Chapter-4
DOING EXPERIMENT USING STAGE

4.1) about the experiment and new stage design

In experiment we have to bend and stretch a thin substrate (perovskite super capacitor). On the basis of experiment requirement design of the stage is changed. To make instrument handier, I had separated out the controller from the stage. There is a separate box for controller. Stage and controller are connected via RS232 cable.

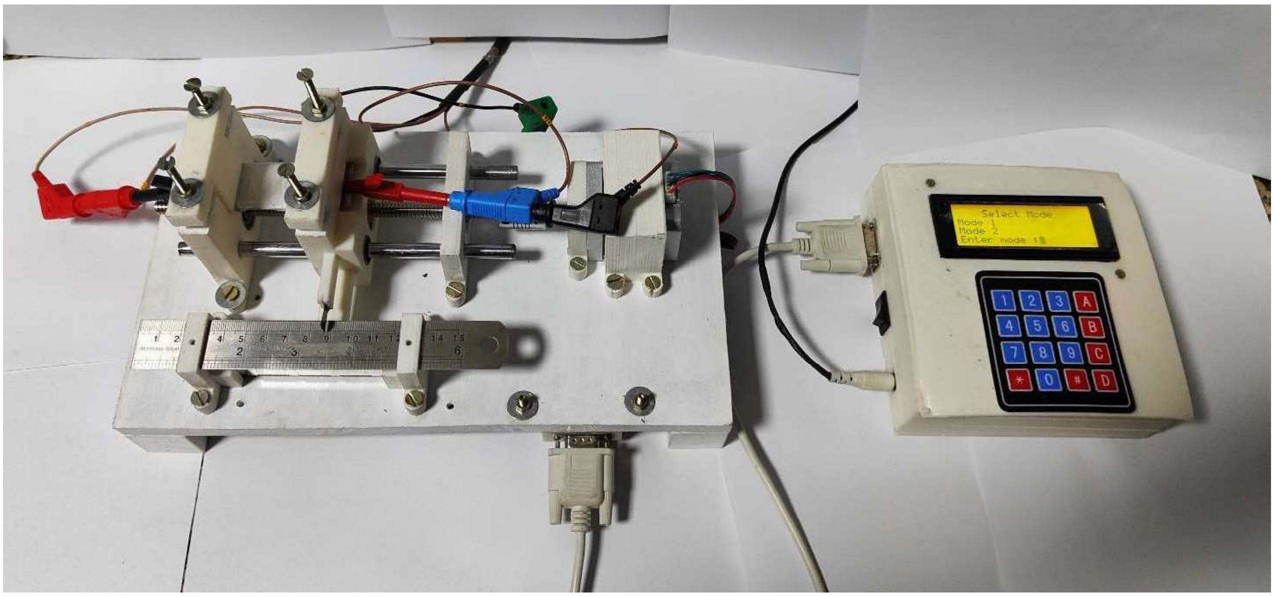

Fig.4.1 – New design of stage

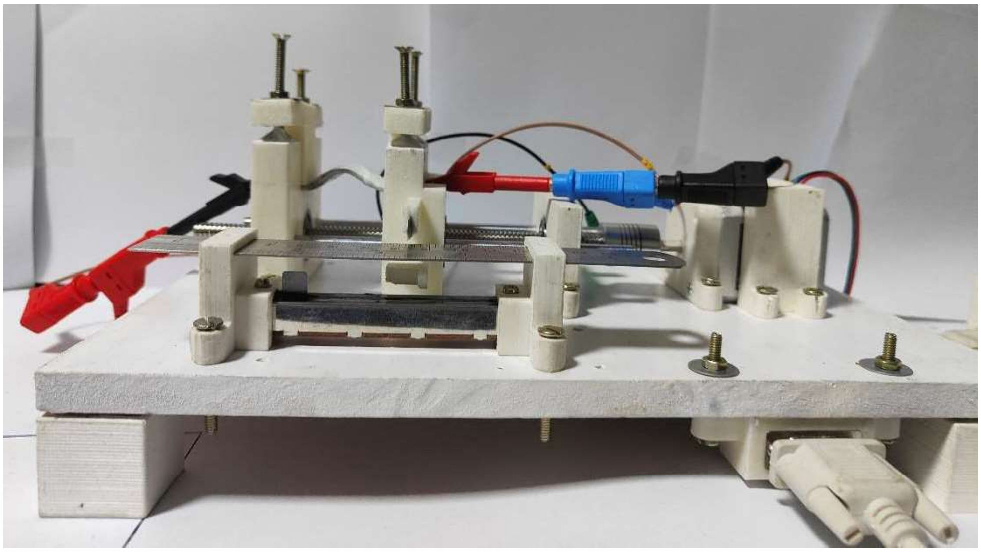

Fig.4.2 – Substrate bending experiment

Fig.4.3 – Experiment setup

4.2 Experiment results

Device flexibility capacitance measurement

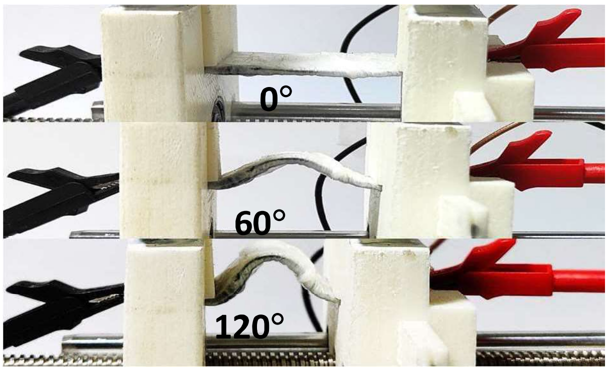

Figure 4.4 (a) Flexible device at different bending angles on stage

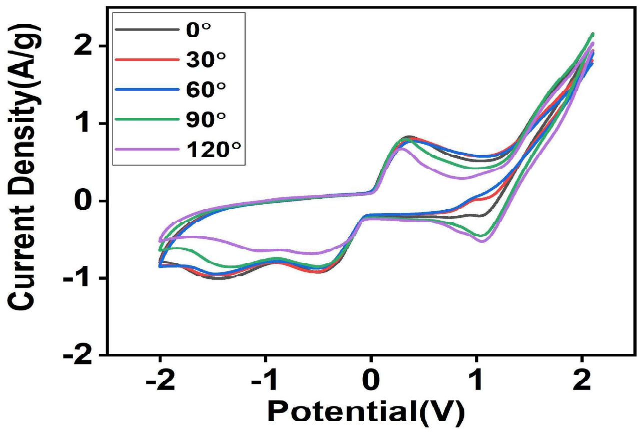

Figure 4.4 (b) Cyclic Voltammetry curve for different bending angles

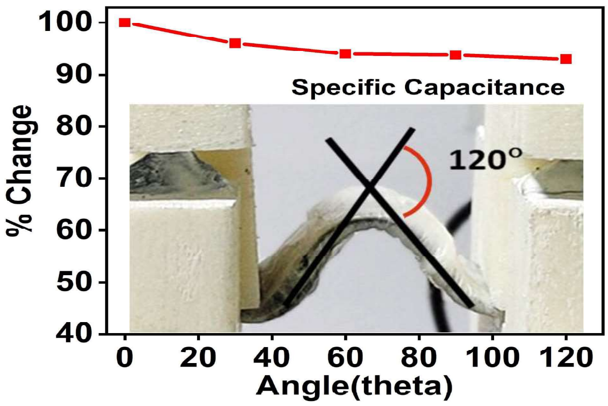

Figure 4.4 (c) Percentage change in Capacitance with different bending angles

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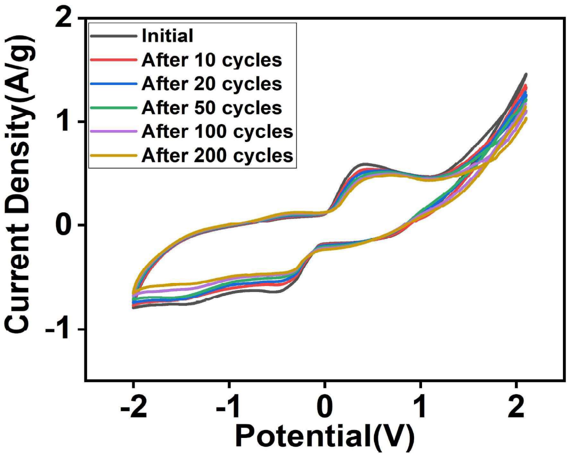

Figure 4.4 (d) Cyclic Voltammetry curve for different bending cycles

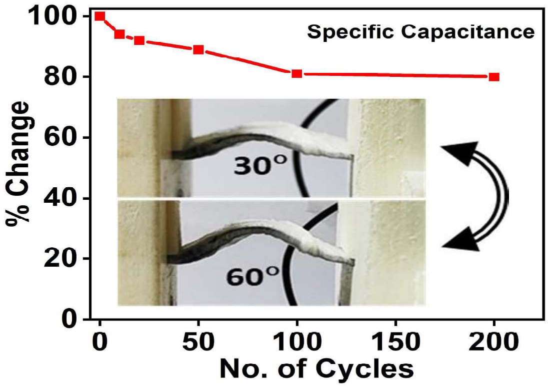

Figure 4.4 (e) Percentage change in Capacitance with different bending cycles

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Fig.3.7	https://en.nanotec.com/products/stepper-gearbox
Fig.3.8	https://www.linearmotiontips.com/what-is-stepper-motor-resonance-and-how-can-it-be-avoided/
Table 1	https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2132

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