# A Compact Material Modulus Measurement Instrument

by

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# Chapter 1

# Introduction

## 1.1 Background and Objective

Soft materials, such as hydrogels and polymers, play a crucial role in various applications, including biomedicine, protective coatings, and electronics. Accurate mechanical characterization of these materials is essential for their effective design and implementation. However, current measurement systems face significant challenges in ensuring precision. On the other hand, strain gauge based Wheatstone bridge is applied in sensing system. The zero shift of the Wheatstone bridge and the Johnson–Nyquist noise of the resistors may leads to measurement inaccuracy. Electromagnetic Interference will also generate significant noise. Since the circuit will integrate ADC, the refection of magnetic wave of the transmission line may leads to Bit Error Rate. Since measurements always involve errors, multiple measurements are necessary. Manually performing repeated measurements, collecting data, and analyzing results is a tedious task. A user-friendly graphical control and data analysis software will significantly improve efficiency.

The project will develop a macro-scale instrument replicating the functionality of an atomic force microscope (AFM) for measuring the mechanical modulus of soft materials. The mechanical design will feature a precision-controlled indentation system, consisting of a motor-driven lead screw and a specially designed cantilever attached with a spherical probe. At the same time, the circuit should develop an low power EMI reduction system that provide extremely accurate measurements. The circuit will optimize the PCB rounting to eliminate the reflection. A good software system can also reduce the measurement iterations as the software features a user-friendly interface that allows users to perform measurements through simple buttons and input fields while displaying the results in real time. It can correct and analyze data, automatically select the appropriate contact model, and calculate the Young's modulus.

## 1.2 Visual Aid

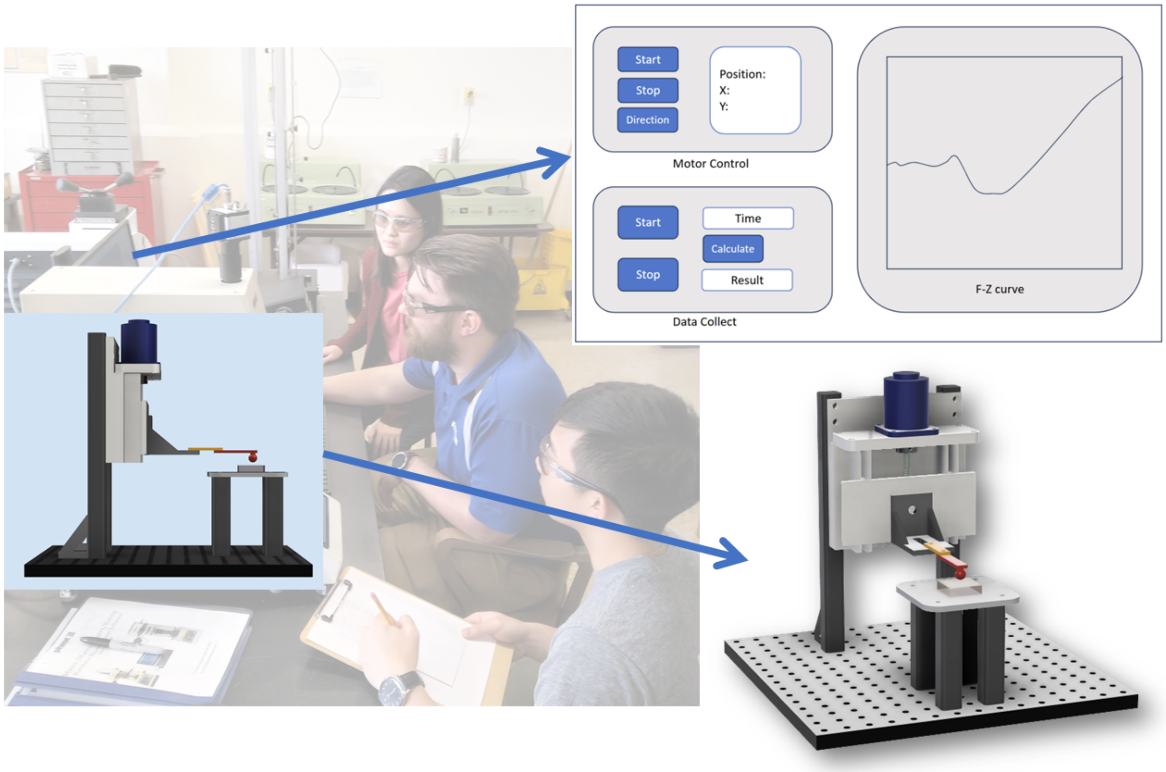



Figure 1.1: Solution in Context

## 1.3 High-Level Requirement List

- The mechanical system shall provide a stable mounting platform and enable precise linear motion with a resolution $\leq 1\ \mu$m, while the cantilever shall have a spring constant at least 10× greater than the sample's effective stiffness under quasi-static contact.
- The circuit should enables accurate signal measurement and processing with minimized EMI. The PCB design ensures proper impedance matching to prevent signal reflection and loss. The control system must precisely control the stepper motor with the required resolution.
- The control system must accurately and completely transmit control and data signals between the strain gauge, upper-level software, and motor driver. The upper-level software must accurately convert the strain gauge signal into force and derive the force-displacement curve based on the stepper motor displacement.

# Chapter 2

# Design

## 2.1 Physical Diagram

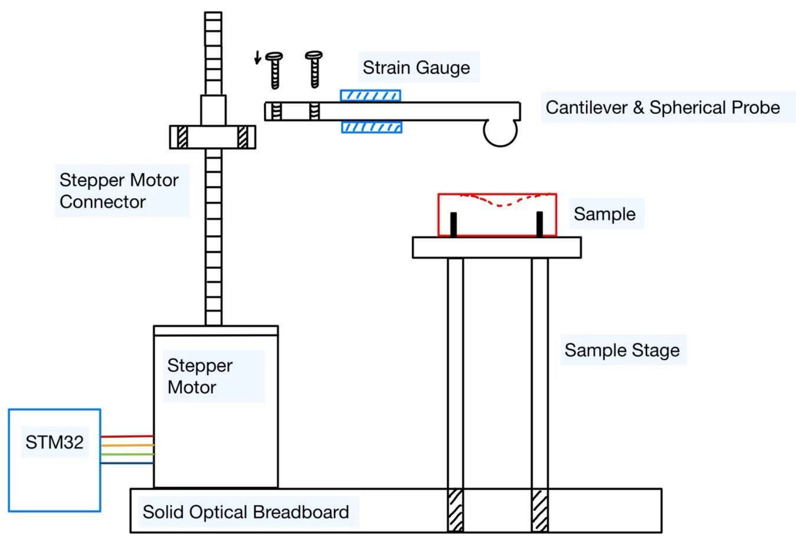



Figure 2.1: Schematic of the Mechanical Design

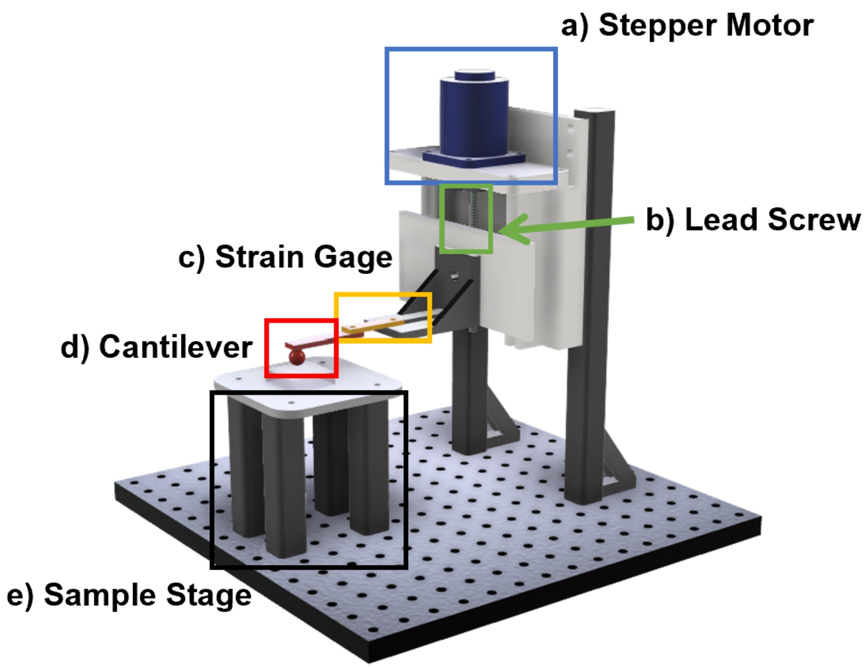
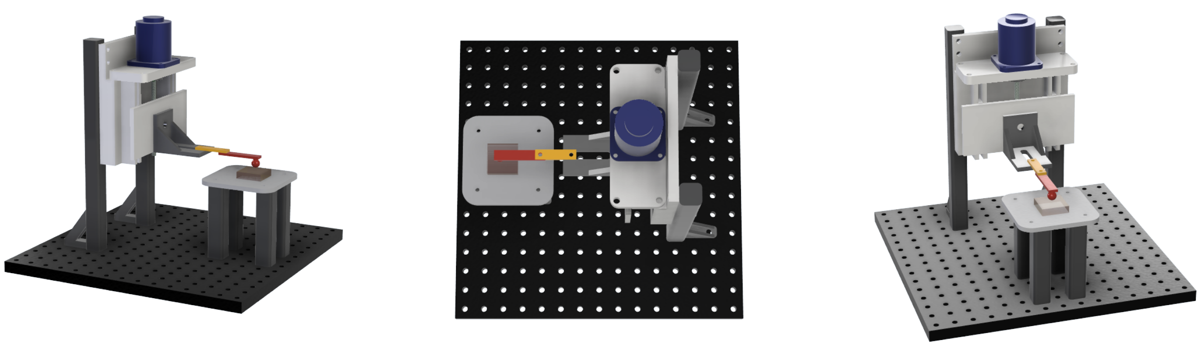



Figure 2.2: CAD Simulation of the Instrument



(a) View1 (b) View2 (c) View3

Figure 2.3: Different Views of CAD

In Figure 2.2, the mechanical design of this system consists of five main components:

(a) **Stepper Motor**: The stepper motor is secured to the motor bracket using four screws. Considering the need for manual adjustments during the initial setup and later connection to the driver, the motor is positioned at a relatively high location on the bracket.

(b) **Lead Screw Coupling**: The lead screw is connected to the motor via a flexible coupling, converting rotational motion into linear motion to drive the selection module.

(c) **Strain Gauge**: The strain gauge is attached to the cantilever beam to detect its minute deformations, converting mechanical strain into voltage signals for further amplification and processing.

(d) **Specially Designed Mechanical Cantilever**: A small sphere is integrally fabricated to the front end of the cantilever via 3D printing. The sphere comes into contact with the sample, causing the cantilever to bend.

(e) **Sample Support Platform**: The platform supporting the sample is fixed using four supporting columns to ensure the sample remains stable during measurement.

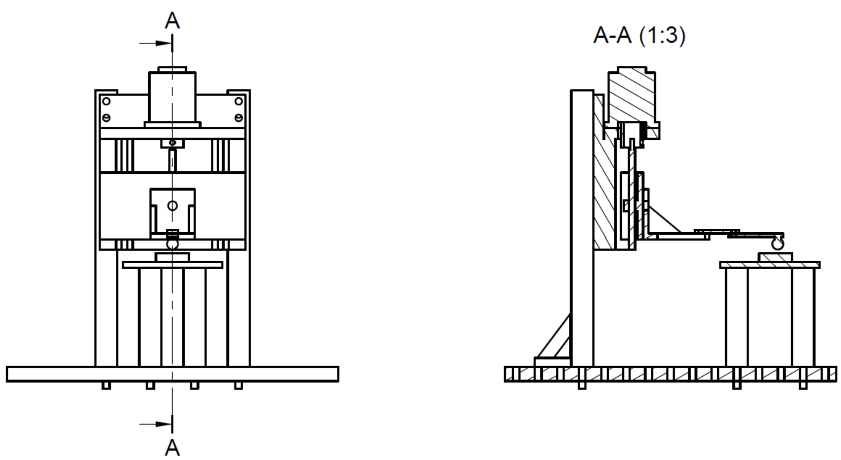



Figure 2.4: Sectional View

Figure 2.4 is the sectional view of the entire instrument, and the following Figures 2.5, 2.6, and 2.7 are orthographic views.

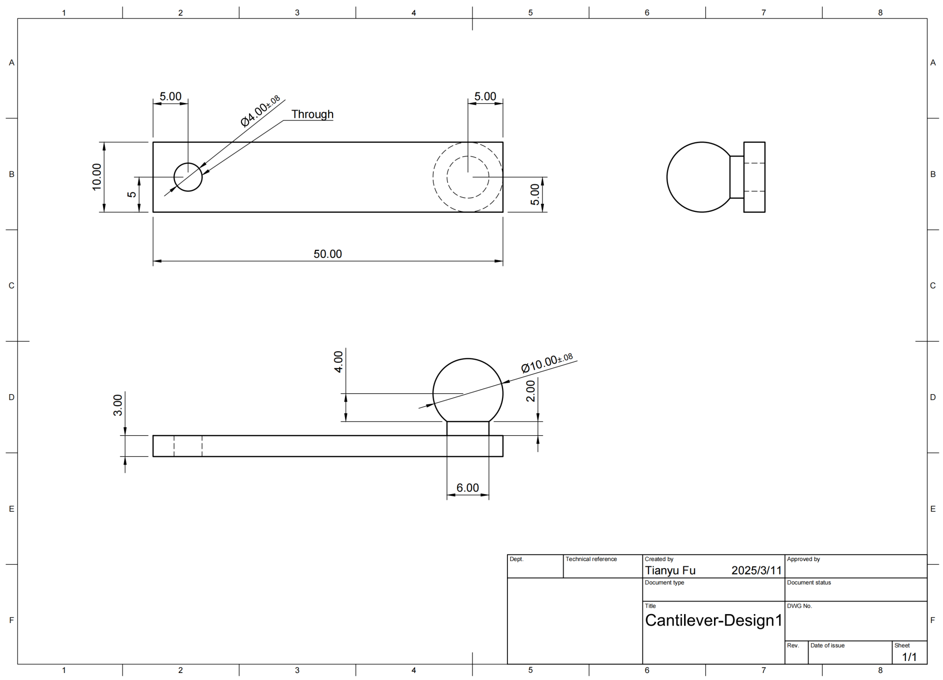



Figure 2.5: Orthographic Views of the Cantilever

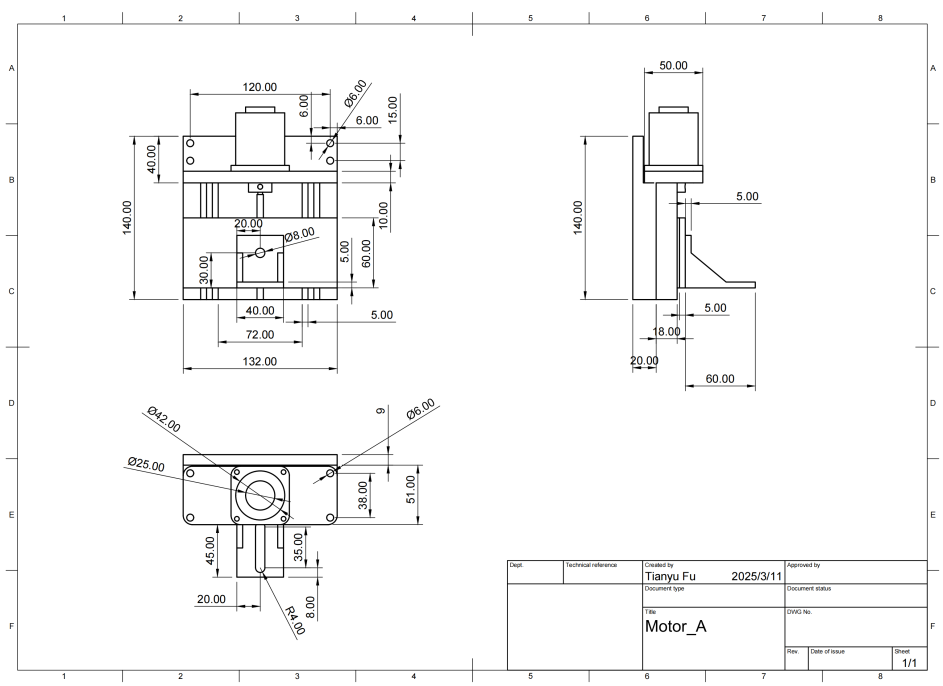



Figure 2.6: Orthographic Views of the Motor Set

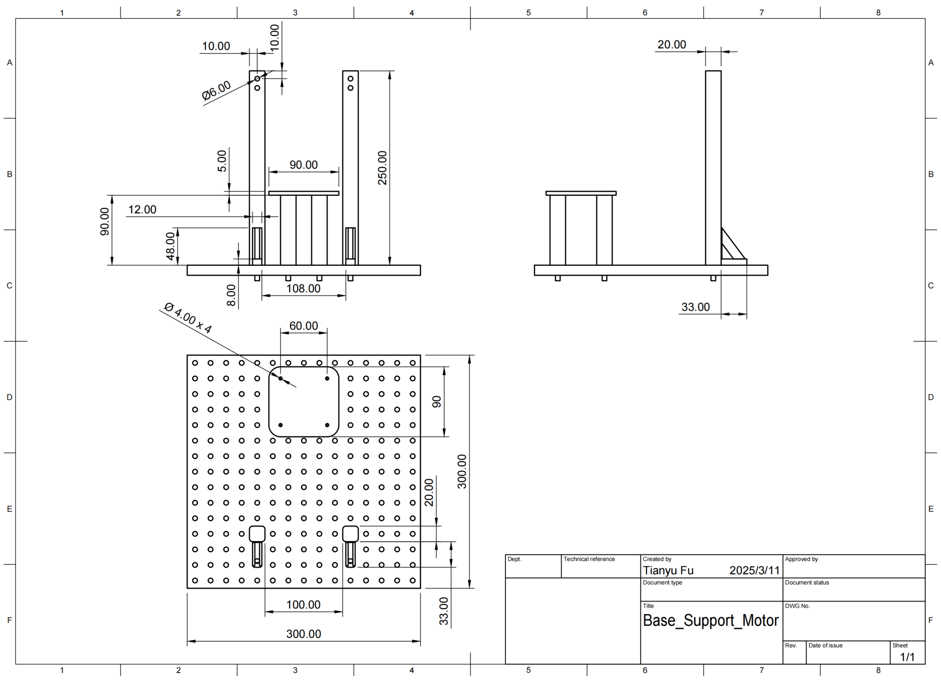



Figure 2.7: Orthographic Views of the Sample Stage and Supporting Part

## 2.2 Block Diagram

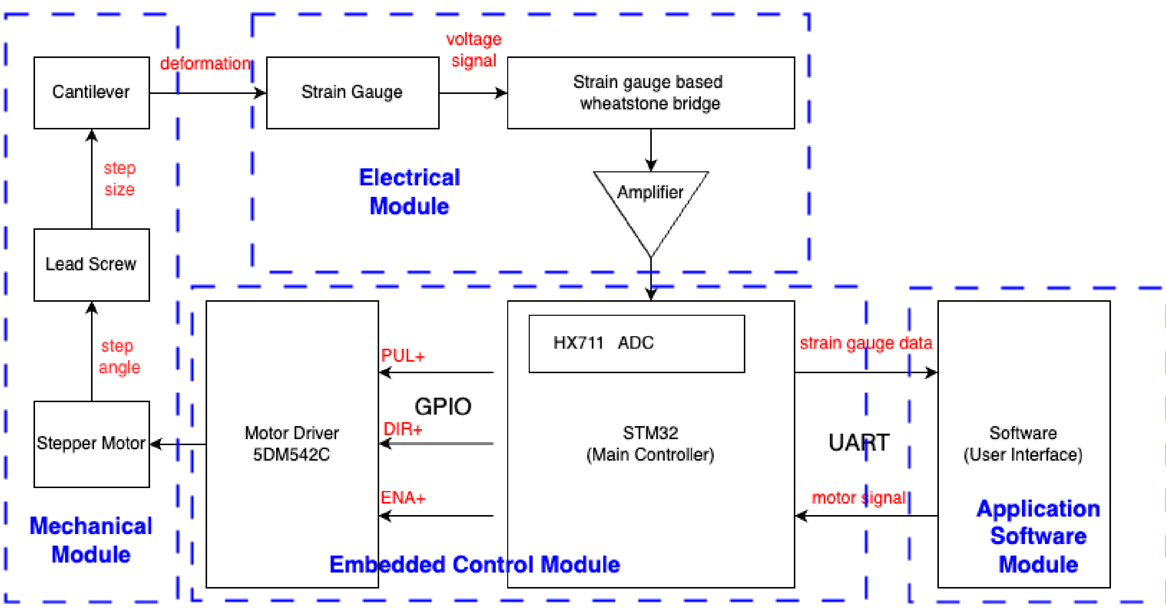



Figure 2.8: Block Diagram

## 2.3 Block Design

### 2.3.1 Mechanical Module

The mechanical module consists of three main components: the stepper motor, the lead screw, and the cantilever. The system operates by converting rotational motion from the stepper motor into linear displacement through the lead screw, ultimately applying force via the cantilever to interact with the sample.

#### Stepper Motor and Screw Coupling

The stepper motor is secured to the motor bracket using four screws. Considering the need for manual adjustments during the initial setup and later connection to the driver, the motor is positioned at a relatively high location on the bracket. The lead screw is connected to the motor via a flexible coupling, converting rotational motion into linear motion to drive the selection module.

| **Requirements** | **Verification** |
|---|---|
| The stepper motor must achieve a linear stepping resolution in the range of $1.0 \pm 0.5$ $\mu$m per step when driven in 1/16 microstepping mode and coupled with a lead screw of 2 mm pitch. | A. Program the motor to move 100 microsteps.<br>B. Use a high-resolution micrometer or laser displacement sensor to measure the actual displacement.<br>C. Verify that the average displacement per step falls within the specified range. |

Table 2.1: Stepper Motor Requirements and Verification Plan

#### Motor and Screw Calculations

We hope the combination of the stepper motor and screw can achieve a step size smaller than 1 micron. The standard step angle for a 5-phase motor is 0.72°, which is much smaller compared to the typical 1.8° step angle of a 4-phase motor available in the market. Furthermore, we will use a motor driver to implement 10x microstepping. Finally, the motor will be combined with a lead screw with a 2mm lead. The step size for each step is calculated as follows:

$$\text{Step} = \frac{\text{Screw Lead}}{\left(\frac{1\text{ rev}}{\text{Step angle}} \times \text{Subdivision}\right)} = \frac{1\text{ mm}}{\left(\frac{360^\circ}{0.72^\circ} \times 10\right)} = 0.2\ \mu m$$

#### Specially Designed Cantilever

A small sphere is integrally fabricated to the front end of the specially designed cantilever via 3D printing. The sphere comes into contact with the sample, applying force to the sample and causing the cantilever to bend.

| **Requirements** | **Verification** |
|---|---|
| 1. The cantilever beam must have an effective spring constant $k$ in the range of 10–15 times larger than that of the material under room temperature and quasi-static loading conditions. | A. Apply known micro-masses (10 g) to the cantilever tip.<br>B. Measure the tip deflection using a laser displacement sensor.<br>C. Repeat for multiple weights and average results. Confirm that the stiffness is within the specified range. |
| 2. The cantilever beam must exhibit a tip deflection of at least 0.1 mm under an applied force in the range of 0.1 N, to ensure a surface strain of at least $5 \times 10^{-4}$, detectable by a strain gauge with a sensitivity of $2.0 \pm 1\%$. | A. Apply a known force via standard weights (10 g) .<br>B. Measure the tip deflection using a laser displacement sensor.<br>C. Verify that the strain falls within the specified range. |

Table 2.2: Cantilever Beam Requirements and Verification Plan

### Cantilever Design Calculations

The spring constant of the cantilever should be much larger than that of the sample.

$$k_c \gg k_s$$

Where $k_c$ represents the spring constant of cantilever, and $k_m$ represents the spring constant of the sample. This is to ensure that the deformation of the cantilever is mainly dominated by the deformation of the measured materials.

$$k_s = \frac{10^5 \times 1.96 \times 10^{-5}}{0.02} = 98 \text{ N/m}$$

The spring constant of the cantilever should be 10 times larger than $k_{s,min}$. The following table contains the parameters designed for the cantilever.

Table 2.3: Different Cantilever Design Parameters

| **Dimension (mm)** | **Length, $l$** | **Width, $w$** | **Thickness, $t$** | **Diameter, $d$** |
|---|---|---|---|---|
| Cantilever 1 | 50 | 10 | 3 | 5 |
| Cantilever 2 | 40 | 10 | 3 | 10 |
| Cantilever 3 | 30 | 10 | 5 | 5 |

The cantilever will be fabricated by 3D printing, using PLA as material. The PLA has an elastic modulus of about 2.5 GPa [1].

$$k_{c,1} = \frac{E_c w t^3}{4 l^3} = \frac{2.5 \times 10^9 \times (0.010 \times 0.003)^3}{4 \times (0.05)^3} = 1350 \text{ N/m}$$

$$k_{c,2} = \frac{E_c w t^3}{4l^3} = \frac{2.5 \times 10^9 \times (0.015 \times 0.003)^3}{4 \times (0.03)^3} = 9365 \text{ N/m}$$

Assuming a minimum detectable resistance change of 0.1%, we have:

$$\frac{\Delta R}{R} \geq 0.001$$

Given a gauge factor (GF) of 2.0, the minimum required strain is:

$$\varepsilon = \frac{\Delta R/R}{\text{GF}} = \frac{0.001}{2.0} = 5 \times 10^{-4}$$

Assuming the strain gauge is bonded to the surface of the cantilever beam and experiences the same strain as the cantilever, the maximum strain typically occurs at the fixed end of the beam. Under the assumption of small deflection, the maximum surface strain at the beam root can be calculated using the following equation:

$$\varepsilon = \frac{3\delta t}{2L^2}$$

Given the required minimum strain of

$$\varepsilon \geq 5 \times 10^{-4}$$

we can rearrange the equation to calculate the minimum required tip deflection $\delta$:

$$\delta \geq \frac{2\varepsilon L^2}{3t}$$

Plug in the parameters of Cantilever 2, it indicated that the vertical deflection of the cantilever should be 178 $\mu$m

### 2.3.2 Electrical Module (analog part)

- **Functionality:** The Wheatstone bridge is used to measure the unknown electrical resistance of the gauge, a Wheatstone bridge is developed using three 220 $\Omega$ resistor. the output signal is processed through an INA125 amplifier to improve the signal-to-noise ratio. The output of the amplifier is transmitted to ADC for digital processing and storage.

- **Requirement 1:** When the strain gauge is not bent, the resistance is 220 $\Omega$, so under normal conditions, the Wheatstone bridge is balanced. If the strain gauge is bent, The magnitude of $V_g$ reflects the change in $R_x$ (the resistance variation of the strain gauge)

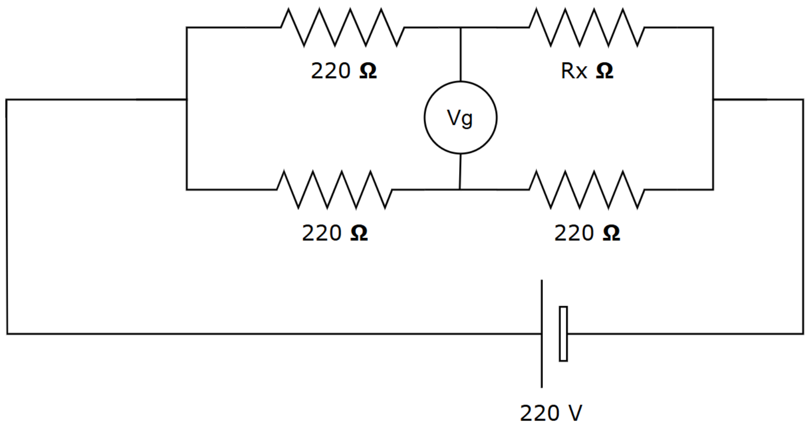



Figure 2.9: Schematic of the Wheatstone bridge

### 2.3.3 Analog to Digital Converter and Programmable Gain Amplifier

The HX711 is a precision 24-bit analog-to-digital converter (ADC) designed specifically for weighing scales and industrial control applications. The output signal is connected to the HX711 to generate the digital data flow. Extra capacitors are added at the analog input node to reduce voltage ripple and ensure isolation

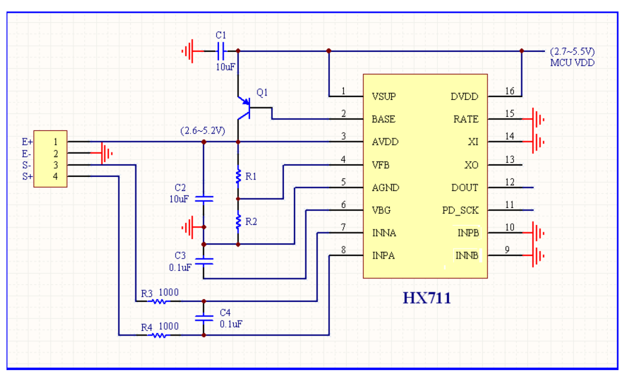



Figure 2.10: Schematic Overview

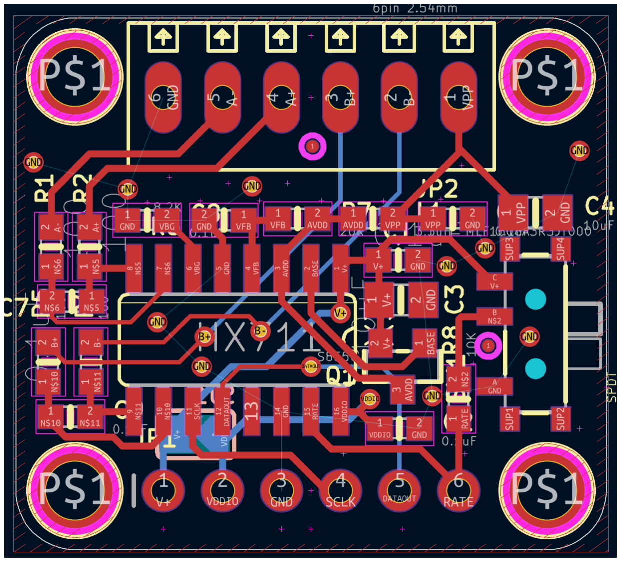



Figure 2.11: PCB layout

The HX711 layout used in this study is based on Adafruit's open-source design [2].

### 2.3.4 Embedded Control Module

The Embedded Control Module is responsible for direct motor control, strain gauge data acquisition, and communication with the upper-level application software via UART. We use STM32F103C8T6 minimum system board as the controller, and the pin assignment and connection is described in the table and figure below:

| Pin | Function | Description |
|---|---|---|
| PB6 | TIM4_CH1 (PUL+) | PWM output to control stepper motor pulse signal |
| PB5 | DIR+ | Digital output for stepper motor direction control |
| PB10 | HX711 DOUT | Receives strain gauge data from HX711 |
| PB11 | HX711 SCK | Clock signal to HX711 (PD_SCK) |
| PA9 | UART TXD | Sends data to PC via CH340 USB-UART |
| PA10 | UART RXD | Receives commands from PC via CH340 USB-UART |
| PB0 | SW2 (Move_Up) | Button input to move motor upward |
| PB1 | SW1 (Move_Down) | Button input to move motor downward |
| PA0 | Red LED (System) | Turns on to indicate system error |
| PA1 | Yellow LED (Status) | Turns on when cantilever contacts sample |

Table 2.4: STM32 Pin Assignment Summary

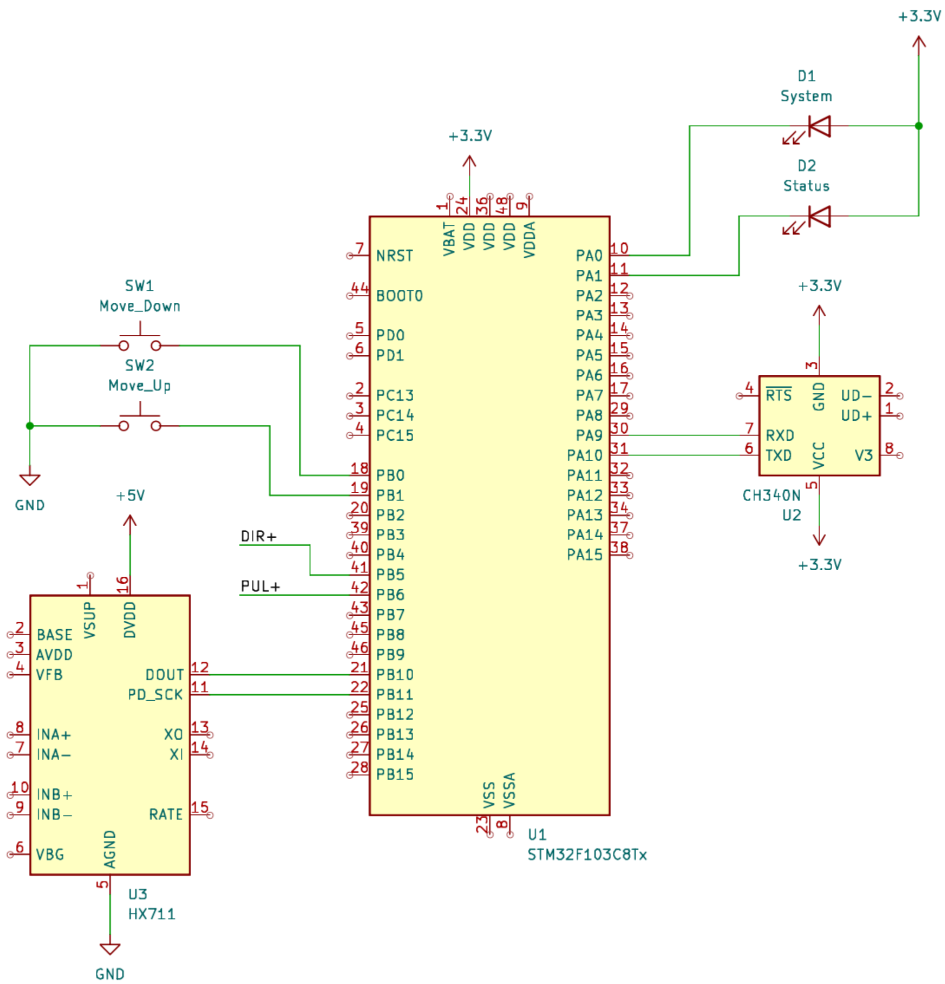



Figure 2.12: Schematic for STM32 Control System

The control system communicates with the host PC via a serial interface. Upon receiving a START command, the stepper motor initiates forward motion to lower the cantilever, while the HX711 module begins sampling strain gauge data and transmitting it over UART. Contact with the material is determined by detecting a significant change in strain, with noise filtering applied. Once contact is detected, the system issues a fixed number of pulses to further displace the cantilever. The motor then reverses direction and continues moving until the strain signal remains stable for a defined duration, indicating separation. During the contact phase—regardless of motor direction—the measurement status LED (PA1) is illuminated. If an error is detected at any point, the system status LED (PA0) is activated. Prior to the start of measurement, PB0 and PB1 buttons can be used to manually control motor direction for cantilever positioning. The logic of the system is designed as a finite state machine (FSM), which has six states, as outlined below:

| State | Actions |
|---|---|
| IDLE | Wait for START command from host PC; User can manually control motor using PB0/PB1 buttons; PA0 and PA1 LEDs are off; HX711 is idle. |
| MOVING_DOWN | Motor moves forward to press cantilever; HX711 starts sampling and transmits data via UART; Monitor strain signal for contact detection. |
| CONTACT_DETECTED | Yellow LED (PA1) is turned on; System continues to apply pressure by sending a fixed number of pulses; Continue transmitting strain data. |
| MOVING_UP | Motor reverses direction; System keeps reading strain data; When signal is stable (no change for a threshold duration), stop motor. |
| FINISHED | Stop motor and data transmission; Turn off yellow LED (PA1); Prepare to return to IDLE state. |
| ERROR | Stop all activities; Turn on red LED (PA0); Await reset or power cycle to return to IDLE. |

Table 2.5: Control System FSM State Actions

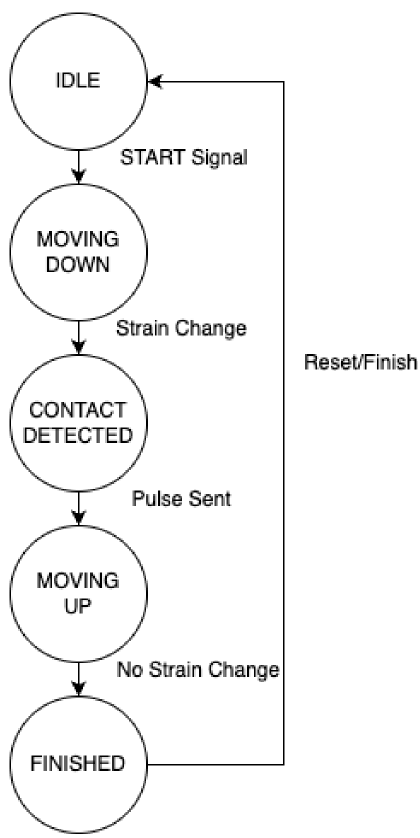



Figure 2.13: Control System FSM

#### Motor Control Module: Timer-Based Stepper Control via GPIO

This module controls the stepper motor through the 5DM542C driver using STM32 GPIO pins. The pulse signal for step control is generated via TIM4, while direction and enable signals are handled via dedicated pins. This enables precise displacement control of the cantilever.

| Requirement | Verification |
|---|---|
| 1. The system must generate pulse signals at 500–2000 Hz with ±2% frequency accuracy to ensure consistent motor speed control. | A. Configure TIM4 to output pulses at test frequencies (e.g., 500 Hz, 1000 Hz, 2000 Hz).<br>B. Use oscilloscope to measure pulse frequency and compare with expected values. |
| 2. Direction change must take effect within 50 ms after command reception. | A. Send direction switch command from PC.<br>B. Use oscilloscope to monitor DIR pin and confirm transition within 50 ms. |

Table 2.6: Motor Control Module Requirements and Verification

#### Data Acquisition Module: Strain Gauge and HX711 Interface

The data acquisition module reads analog strain signals via the HX711 24-bit ADC. The STM32 retrieves digital data via GPIO and transmits it to the PC in real time. This module enables high-resolution force measurements during cantilever-material interaction.

| Requirement | Verification |
|---|---|
| 1. The system must sample strain data at a rate of at least 10 Hz with a resolution of at least 24 bits. | A. Configure HX711 in 10 Hz mode.<br>B. Log output values and validate update rate.<br>C. Confirm 24-bit resolution by analyzing raw digital output range. |
| 2. The measured noise (peak-to-peak) in strain readings under static load must be less than 10 LSB. | A. Place cantilever in unloaded static condition.<br>B. Record 100 data samples.<br>C. Calculate peak-to-peak noise in LSB. Confirm it is less than 10. |

Table 2.7: Data Acquisition Module Requirements and Verification

### 2.3.5 Application Software Module

The Application Software Module controls the overall measurement process through a state machine. It initializes the system, manages user interactions, controls motor movement, and processes force-displacement data. Final results are displayed in the GUI and can be saved to disk.

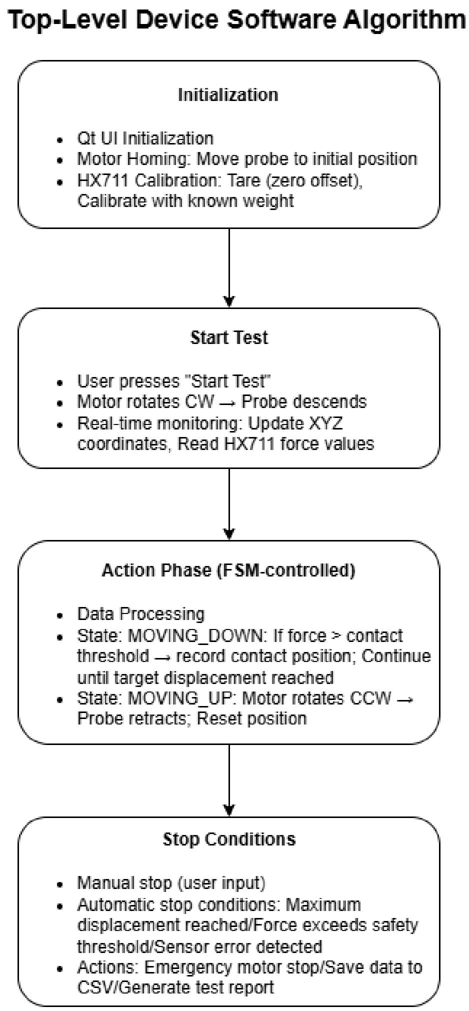



Figure 2.14: Top-Level Device Software Algorithm

It relies on three key submodules to function effectively, as detailed below.

#### Serial Communication Module: QSerialPort and STM32 UART Transmission

The serial communication module establishes a bidirectional data channel between the STM32 microcontroller and the host computer using UART over a USB-to-serial connection. Leveraging the QSerialPort library on the PC side, it enables structured data exchange and real-time control signal transmission. This module ensures reliable data integrity and synchronization between user commands and system responses.

| Requirement | Verification |
|---|---|
| 1. The communication module must achieve bidirectional data transmission at 96000 $\pm 5\%$ baud rate with a maximum data loss rate below 1% during a 60-second continuous test. | A. Connect STM32 and PC via USB-to-UART.<br>B. Transmit a predefined 1KB data packet from PC to STM32 and vice versa at 96000 baud.<br>C. Record the number of successfully received bytes. Compute error rate. Confirm it is less than 1%. |
| 2. The system must correctly parse and respond to structured command frames of 8 bytes, and update internal status within 100 ms of receiving a valid frame. | A. Use QSerialPort to send valid/invalid 8-byte command frames to STM32.<br>B. Monitor UART response time with oscilloscope or logic analyzer.<br>C. Confirm valid commands are parsed and system reacts (e.g., toggles GPIO) within 100 ms. |

Table 2.8: Serial Communication Module Requirements and Verification

**Data Processing Module: Force Calculation and Young's Modulus Estimation**

The data processing module receives raw sensor data from the STM32, including strain gauge readings and displacement values. It computes the applied force using calibrated transformation equations and estimates the Young's modulus of the test material through a pre-trained machine learning model. This module serves as the analytical core of the system, translating low-level signals into meaningful mechanical properties.

| Requirement | Verification |
|---|---|
| 1. The force conversion algorithm must yield force values with less than $\pm 10\%$ error when compared against standard weights. | A. Apply known calibrated weights to sensor.<br>B. Record strain gauge voltage and compute force using algorithm.<br>C. Compare computed force to ground truth. Verify relative error $< 5\%$. |
| 2. The Young's modulus estimation model must produce results within $\pm 10\%$ of the known reference values for at least 3 different materials. | A. Run tests on three calibration materials with known Young's modulus.<br>B. Capture force-displacement curve and feed into ML model.<br>C. Compare output modulus with known values. Ensure all deviations less than 10%. |

Table 2.9: Data Processing Module Requirements and Verification

### User Interface Module: Qt-Based GUI for System Control and Visualization

Our interface is developed using Qt and provides intuitive controls for motor movement, parameter configuration, and data visualization. It displays real-time force-displacement plots and allows the user to initiate material testing procedures. Through this interface, users interact with the system efficiently, monitor results live, and export data for further analysis.

| Requirement | Verification |
|---|---|
| 1. The GUI must refresh the force-displacement graph at a minimum rate of 10 Hz with less than 200 ms latency between data arrival and display. | A. Simulate serial data input at 10 Hz using a test script.<br>B. Use a screen recording tool with timestamp overlay to measure latency.<br>C. Confirm display is updated within 200 ms after each data point. |
| 2. The user must be able to control motor power and direction through the GUI, with correct serial commands sent upon each interaction. | A. Click each control on the GUI.<br>B. Use a serial monitor to observe outgoing command format.<br>C. Verify commands match specification and motor responds accordingly. |
| 3. The user must be able to save the data of the F-Z curves after clicking save and get the result of the elastic modulus calculated from current curve after clicking calculate. | A. Click the "Save" button after generating an F-Z curve.<br>B. Check the file system for a correctly named output file containing time-stamped force and displacement data.<br>C. Click the "Calculate" button and verify that a Young's modulus value is displayed, matching the result from an independent offline analysis within 5% error. |

Table 2.10: User Interface Module Requirements and Verification

## 2.4 Tolerance and Risk Analysis

### 2.4.1 Tolerance Analysis

#### Mechanical Design

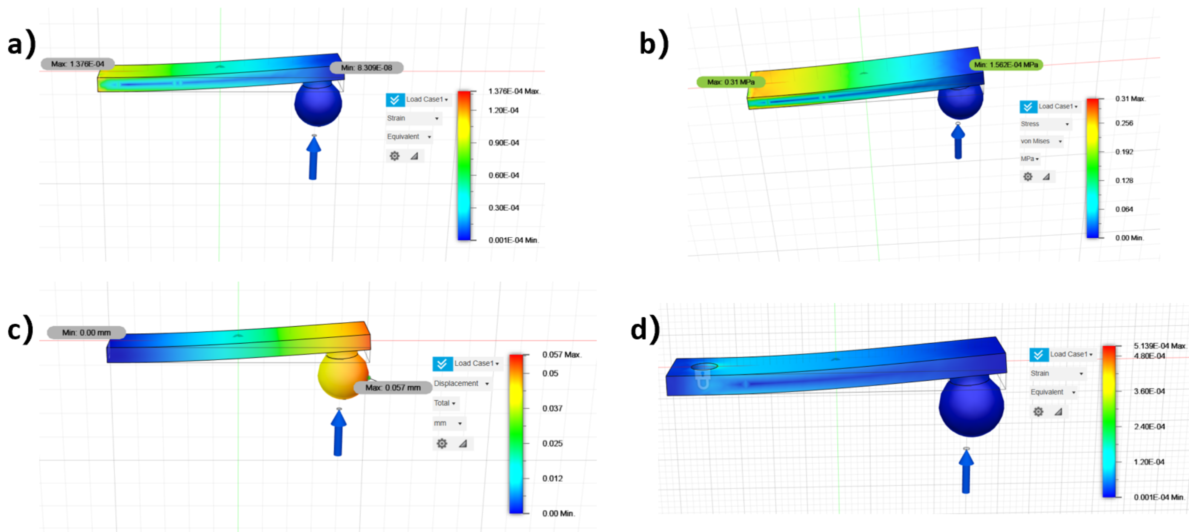



Figure 2.15: Finite Element Analysis. a) strain distribution. b) stress distribution. c) Displacement distribution. d) strain distribution (original model).

The simulation of the cantilever finite element analysis is conducted under a vertical force of 0.1 N. The results indicate that the maximum strain occurs at the fixed end of the beam, with a value of $1.376 \times 10^{-4}$. The maximum deflection is 0.057 mm, and the safety factor is 15.

The printing accuracy of the cantilever will directly affect its dimensions, such as the beam's length, width, and thickness. This will, in turn, affect its mechanical properties, such as stiffness and sensitivity to deflection under force. Given that the printer's tolerance is $\pm$0.08mm, it will lead to slight variations in the behavior of the beam. However, this could still be within acceptable limits depending on the precision required for the force measurement.

The combination of the stepper motor and lead screw achieves a positional accuracy of 0.01mm, ensuring precise positioning of the tool or sample. With a repeatability of $\pm$0.001mm , the system can consistently perform the same action with minimal error. However, there is a lost motion of 0.003mm, which introduces small errors during the transmission process, potentially affecting the consistency of force application or displacement.

## ADC HX711

| Parameter | Conditions and Description | Min | Typ | Max | Unit |
|---|---|---|---|---|---|
| Full-Scale Differential Input Range | V(inp) - V(inn) | | ±0.5(AVDD/GAIN) | | V |
| Effective Number-of-Bits (1) | Gain = 128, Rate = 10Hz | | 19.7 | | Bits |
| Noise-Free Bits (2) | Gain = 128, Rate = 10Hz | | 17.3 | | Bits |
| Integral Nonlinearity (INL) | Full-scale ratio | | ±0.001 | | % of FSR |
| Common Mode Voltage Range | | AGND + 1.2 | | AVDD - 1.3 | V |
| Output Data Rate | Internal Oscillator, RATE = 0<br>Internal Oscillator, RATE = DVDD<br>External Clock or Crystal, RATE = 0<br>External Clock or Crystal, RATE = DVDD | 10 | <br>80<br>$f_{clk}$/1,105,920<br>$f_{clk}$/138,240 | | Hz |
| Output Data Format | Binary Code | 800000 | | 7FFFFF | HEX |
| Output Settling Time (3) | RATE = 0<br>RATE = DVDD | | 400<br>50 | | ms |
| Input Offset | Gain = 128<br>Gain = 64 | | 0.1<br>0.2 | | mV<br>mV |
| Input Noise | Gain = 128, RATE = 0<br>Gain = 128, RATE = DVDD | | 50<br>90 | | nV(rms)<br>nV(rms) |
| Temperature Coefficient | Input Offset Drift (Gain = 128)<br>Gain Drift (Gain = 128) | | ±12<br>±7 | | nV/°C<br>ppm/°C |
| Common Mode Rejection Ratio | Gain = 128, RATE = 0 | | 100 | | dB |
| Power Supply Rejection Ratio | Gain = 128, RATE = 0 | | 100 | | dB |
| Output Reference Voltage ($V_{BG}$) | | | 1.25 | | V |
| External Clock or Crystal Frequency | | 1 | 11.0592 | 20 | MHz |
| Power Supply Voltage | DVDD<br>AVDD, VSUP | 2.6<br>2.6 | | 5.5<br>5.5 | V<br>V |
| Analog Power Supply Current | Normal Operation<br>Power Down | | 1500<br>0.5 | | μA<br>μA |
| Digital Power Supply Current | Normal Operation<br>Power Down | | 100<br>0.2 | | μA<br>μA |

Table 2.11: Electrical Characteristics

$$\begin{aligned} \text{Gain} &= 128 \\ V_{\text{ref}} &= 3.3\,\text{V} \\ \text{Input}_{\text{allow}} &= \frac{V_{\text{ref}}}{\text{Gain}} = \frac{3.3\,\text{V}}{128} \approx 25.78\,\text{mV} \\ \text{19-bit resolution} &= \frac{\text{Input}_{\text{allow}}}{2^{19}} \approx \frac{25.78\,\text{mV}}{524288} \approx 0.049\,\mu\text{V} \end{aligned}$$

### Wheatstone bridge noise simulation @300K

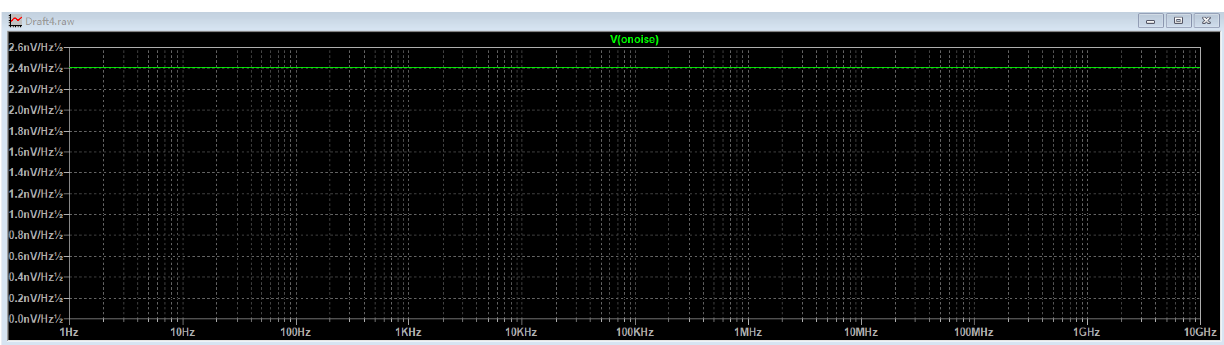



Figure 2.16: noise simulation at 300K

the thermal noise for Wheatstone bridge is 2.6nV, below the detectable range of the ADC, therefore the thermal noise will not largely affect the circuit output.

### 2.4.2 Risk Analysis

- **Mechanical components:** Mechanical components such as the motor, lead screw, and bearings may experience wear, which could affect the system's performance. The accumulation of wear may lead to increased backlash and decreased repeatability. Besides, changes in temperature, humidity, or vibrations can affect the mechanical parts of the system. For example, thermal expansion could alter the geometry of the lead screw or cantilever beam, leading to small changes in force application.

  Regular calibration of the system will help compensate for small mechanical deviations and lost motion. Using high-precision components and low-backlash lead screws can reduce the effects of mechanical inaccuracies. The instrument will be maintained in the ambient environment to Ensure stable environmental conditions, which can help minimize external influences on the system.

- **Digital system** The QSerialPort block is an important yet sensitive part of the system. If there are issues like data loss, delays, or errors, the instrument will fail to provide accurate results. The QSerialPort must support baud rates matching the STM32's UART settings (e.g., 115200 bps or higher) to ensure that both command and sensor data are transmitted in real-time without significant delay. The acceptable tolerance for data loss or packet errors should be minimal (e.g., less than 0.5% packet loss per transmission). The communication latency between the Qt interface and STM32 must be low to maintain real-time interaction with the motor and accurate sensor readings. A tolerance of less than 10 milliseconds delay is acceptable.

# Chapter 3

# Cost Analysis

| Name | Model | Price (RMB) |
|---|---|---|
| Optical Breadboard | 300x300x13 M6 | 252 |
| Strain Gage | 350-3AA/120, 120-3AA/1K | 30 |
| HX711 | / | 4 |
| Stepping Motor & Screw Stage | 28*32 0601/0802 100–200mm | 495 |
| Stepper Motor Driver | 5DM542C | 340 |
| STM32 | STM32F103C8T6 | 34 |
| ADALM1000 | / | / |
| Aluminum Profile | 2020L-1.5 (1m) | 10.9 |
| 3-way Right Angle Connector | 2020*4 | 6.4 |
| **TOTAL** | | **1172.3** |

Table 3.1: Bill of Materials for Mechanical and Electronic Components

# Chapter 4

# Schedule

| Week | Task | Responsibility |
|---|---|---|
| 2/24/25 | Discuss design requirements with professor | All |
| 3/3/25 | Finalize schematic diagram of mechanical system | Tianyu Fu |
| | Completed RFA and team contract | All |
| | Select and purchase key mechanical components | All |
| 3/10/25 | Complete detailed CAD model of motor support structure, screw stage, cantilever support and sample holder platform | Tianyu Fu |
| | Conduct experiments with the strain gauge and design the Wheatstone bridge circuit | Ziyi Lin |
| | Explore the software architecture and draft the system interface design | Kongning Lai & Yunzhi Lu |
| | Complete the PCB design assignment | All |
| | Compose the proposal | All |
| 3/17/25 | Design cantilever geometries optimized for 3D printing | Tianyu Fu |
| | Begin 3D printing of initial cantilever prototypes | Tianyu Fu |
| | Develop submodules of the control system | Kongning Lai & Yunzhi Lu |

Table 4.1: Project Schedule and Task Allocation (Part 1)

| Week | Task | Responsibility |
|---|---|---|
| 3/24/25 | Assemble screw stage and cantilever support | Tianyu Fu |
| | Begin calibration tests for cantilever deflection (strain) and force using a balance | All |
| | Use buttons to control GPIO output of PWM pulse and DIR signals | Kongning Lai |
| | Use serial commands to control GPIO output of PWM pulse and DIR signals | Kongning Lai |
| | Improve the interface and start connecting serial ports | Yunzhi Lu |
| | Test the stepper motor driver voltage/current | All |
| 3/31/25 | Assemble the motor mount and sample holder base | Tianyu Fu |
| | Connect stepper motor and driver for initial testing | Ziyi Lin |
| | Test linear motion of the cantilever mechanism | Ziyi Lin |
| | Connect strain gauge, HX711, and STM32 microcontroller | Ziyi Lin & Kongning Lai |
| | Test ADC conversion and data reading functionality | Ziyi Lin |
| | Implement serial communication between STM32 and the Qt interface | Yunzhi Lu |
| | Implement the elastic modulus estimation algorithm in Python | Yunzhi Lu & Kongning Lai |
| 4/7/25 | Refine motion test for the cantilever stage | Ziyi Lin |
| | Write the design document | All |
| 4/14/25 | Continue calibration of cantilever strain and force with a balance | Ziyi Lin |
| | Implement data transfer between STM32 and QT, along with real-time curves plotting | Yunzhi Lu |
| 4/21/25 | Fine-tune alignment and motion control of the screw stage | Tianyu Fu |
| | Integrate machine learning methods into the elastic modulus estimation algorithm | Kongning Lai & Yunzhi Lu |
| 4/28/25 | Optimize cantilever design (geometry, stiffness, material) | Tianyu Fu |
| | Integrate Python scripts and models into the QT framework | Yunzhi Lu |
| | Integrate mechanical, electrical, and software modules into system | All |
| 5/5/25 | Conduct experiments on zero shift and balance resistance | All |
| 5/12/25 | Calibrate cantilever using known weights or displacement | All |
| 5/19/25 | Document test results and apply final design refinements | All |
| 5/26/25 | Write final report | All |
| | Prepare for team rehearsals and final project presentation | All |

Table 4.2: Project Schedule and Task Allocation (Part 2)

# Chapter 5

# Ethics and Safety

Our project has several potential safety concerns and ethics considerations. First, we are using a 9V rechargeable battery, which could lead to short circuits, potentially leading to fire, or injury. Additionally, the strain gauge we are using has a voltage tolerance of approximately 10V, making it possible for electrical breakdown, which could directly cause a short circuit. To solve this issue, we will incorporate protective resistors in the circuit design and ensure that at least two people are present during each experiment for safety supervision.

Another safety concern involves our use of 3D printing technology to construct the cantilever beam. The printer nozzle operates at high temperatures, with the hot end reaching up to 300°C, posing a risk of burns. To prevent unnecessary injuries, we will wear protective gloves when handling the 3D printer and ensure careful operation to avoid direct contact with the heated components.

Additionally, most plastics release harmful gases when burned, and 3D printing is no exception. In particular, when using ABS and other engineering plastics, high temperatures may lead to the emission of xylene and other toxic substances. To mitigate the risks associated with hazardous emissions during 3D printing, we will wear protective masks and ensure proper ventilation in the workspace.

Last, the mechanical components will also be designed with safety in mind, following guidelines provided by the Occupational Safety and Health Administration (OSHA) and ISO 12100 for the safe design of machinery. This project adheres to various ethical codes, including those outlined by the American Society of Mechanical Engineers (ASME) and Institute of Electrical and Electronics Engineers (IEEE). These ethical codes emphasize transparency, safety, and the responsibility to ensure that engineering practices are conducted with the welfare of society and the environment in mind. Additionally, the project will reference ISO 13485 standards for medical device design, ensuring that safety, quality, and ethical considerations are incorporated into the final product.

# References

[1] Y. Zhao, Y. Chen, and Y. Zhou, "Novel mechanical models of tensile strength and elastic property of fdm am pla materials: Experimental and theoretical analyses," *Materials Design*, vol. 181, p. 108089, 2019.

[2] Adafruit, "Adafruit-hx711-24-bit-adc-pcb: Pcb files for the adafruit hx711 24-bit adc," https://github.com/adafruit/Adafruit-HX711-24-bit-ADC-PCB/, 2024, accessed: 2025-04-14.