A Compact Material Modulus Measurement Instrument

by

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Objective and Background

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.

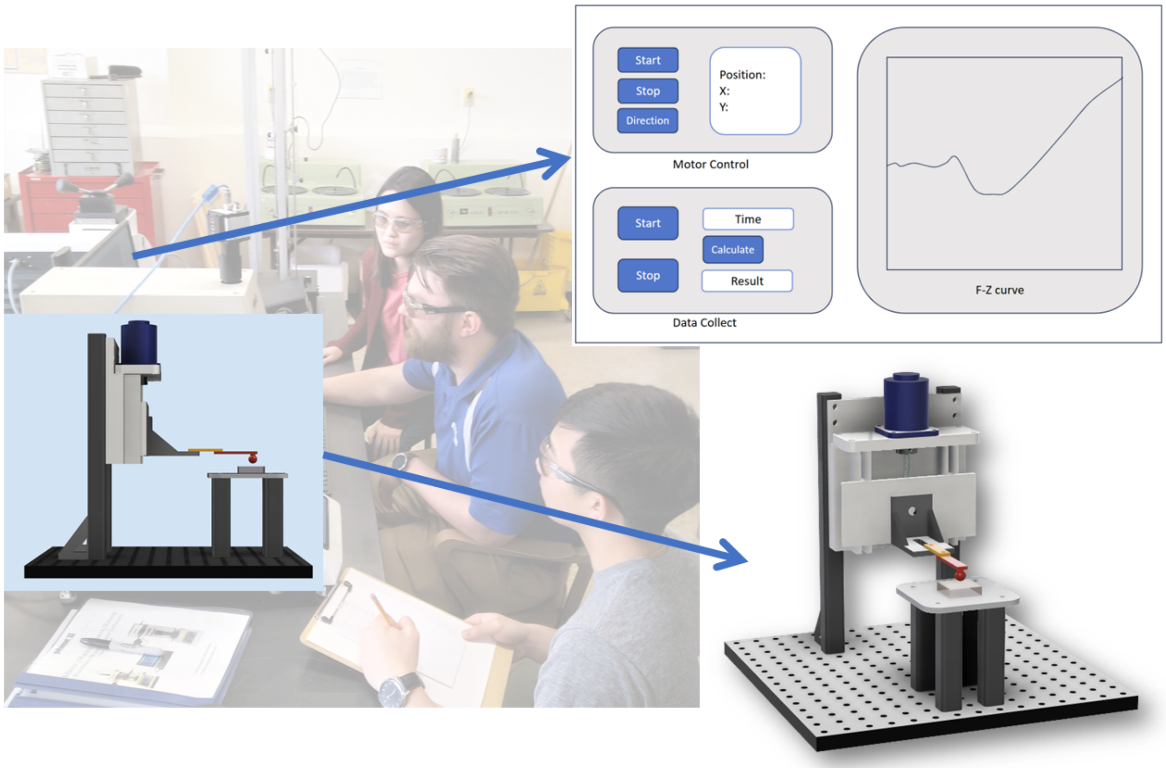


Figure 1.1: Solution in Context: User Interface and Instrument

1.2 High-Level Requirement List

- **Mechanical**: The mechanical design must include a stable platform for securely mounting the stepper motor and cantilever. The stepper motor, connected to a lead screw, must achieve a stepping resolution of 1 μm or less through microstepping. Additionally, the cantilever beam must be highly sensitive to small deformation, with a spring constant 10 times larger than the contact spring constant of the sample.

- **Circuit**: 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.

- **Control system**: 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

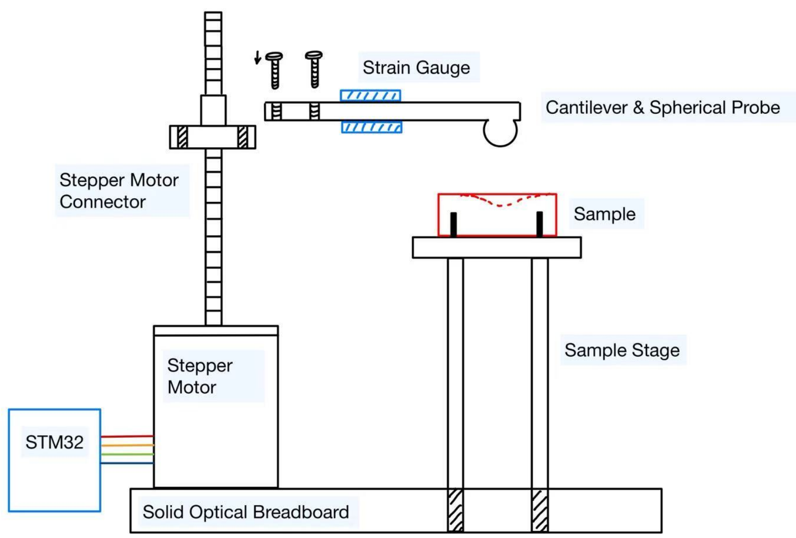


Figure 2.1: Schematic of the Mechanical Design

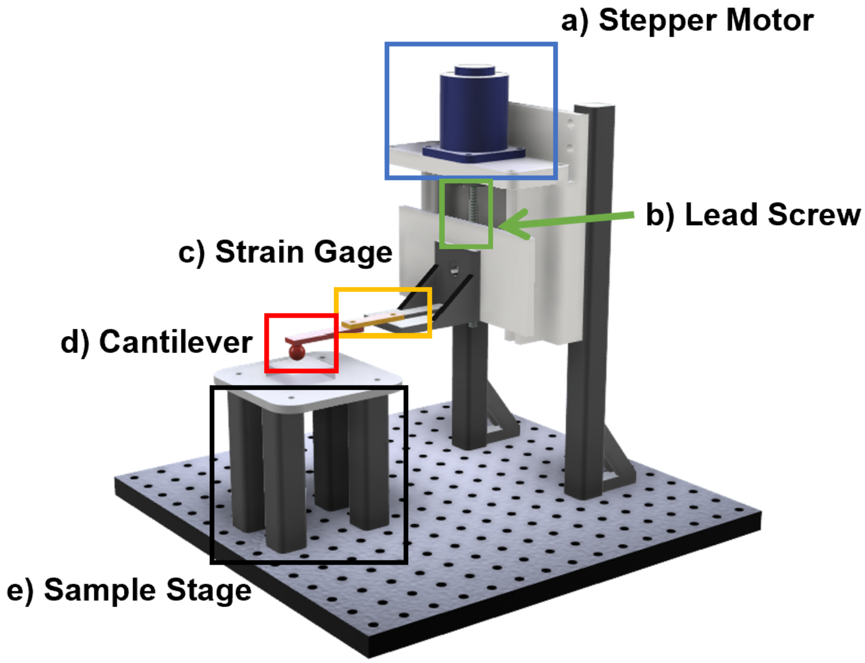
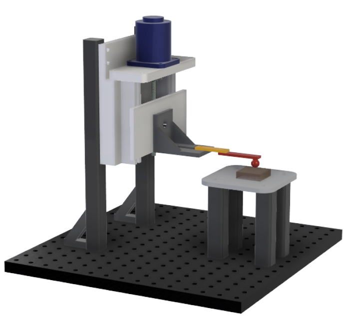
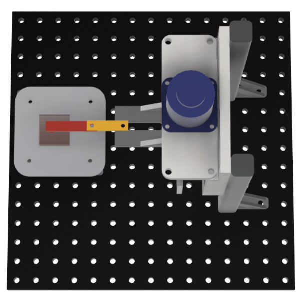


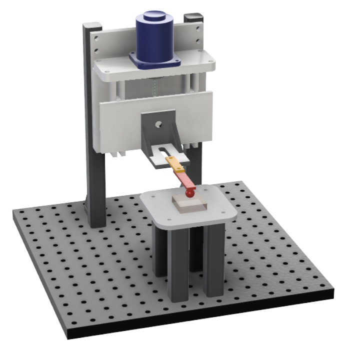
Figure 2.2: CAD Simulation of the Instrument



(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.

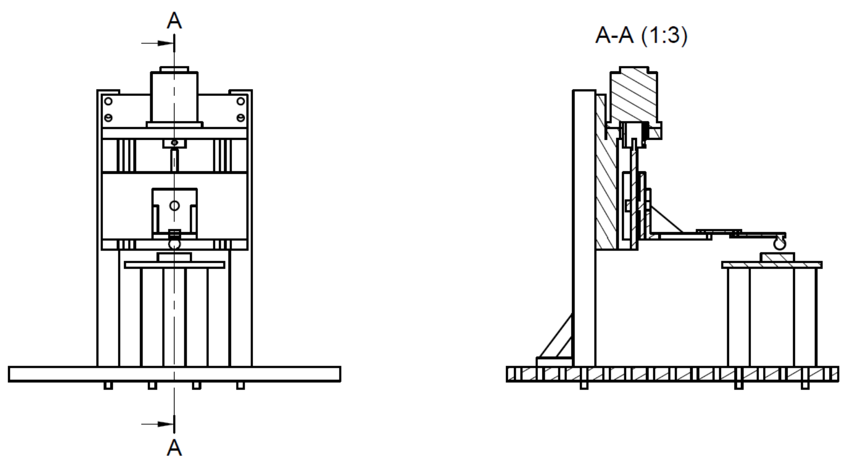


Figure 2.4: Sectional View

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.

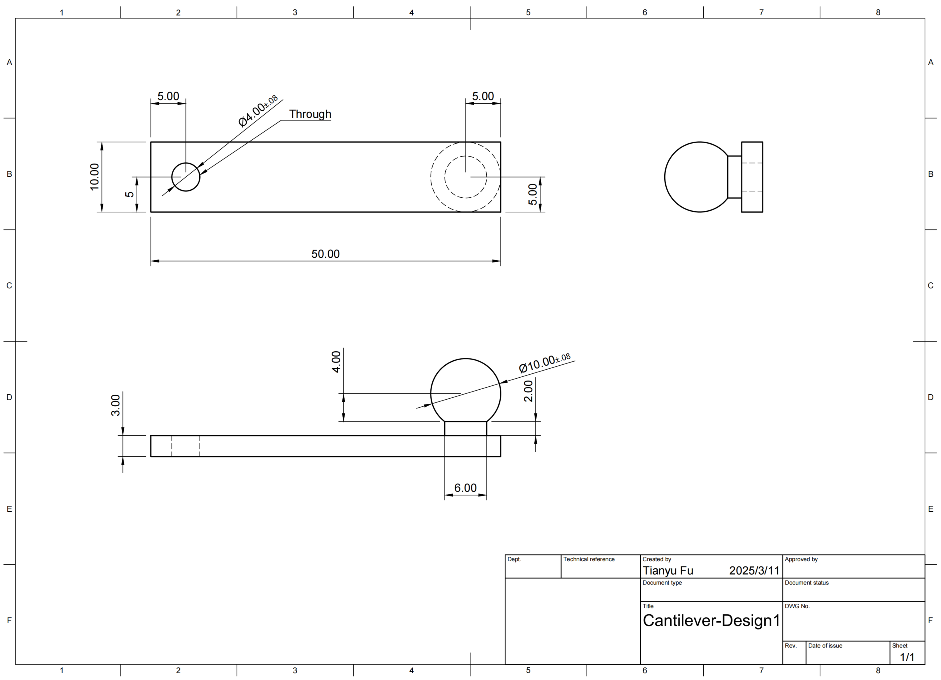


Figure 2.5: Orthographic Views of the Cantilever

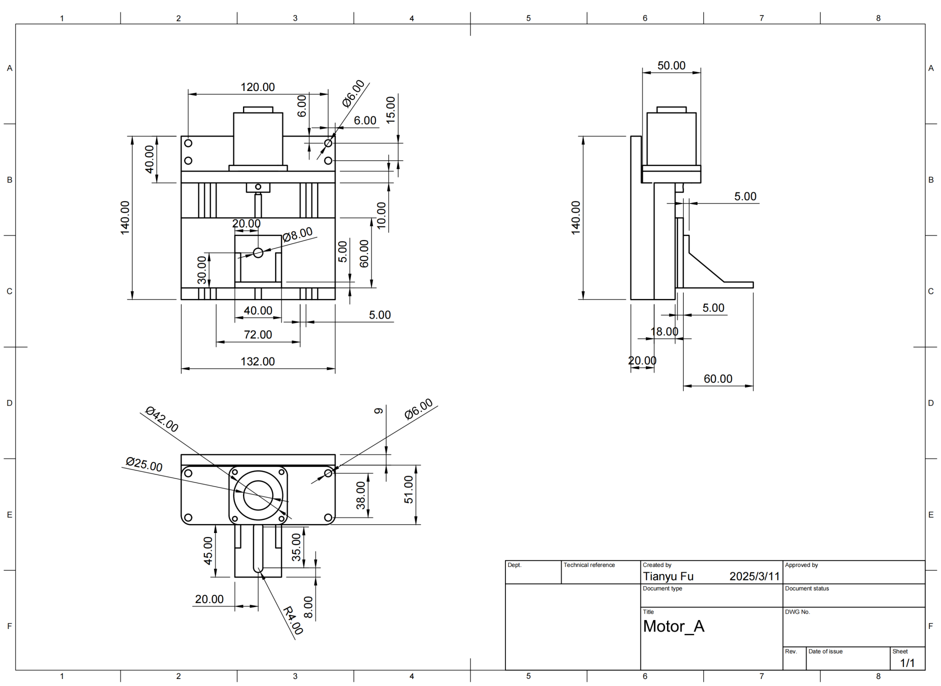


Figure 2.6: Orthographic Views of the Motor Set

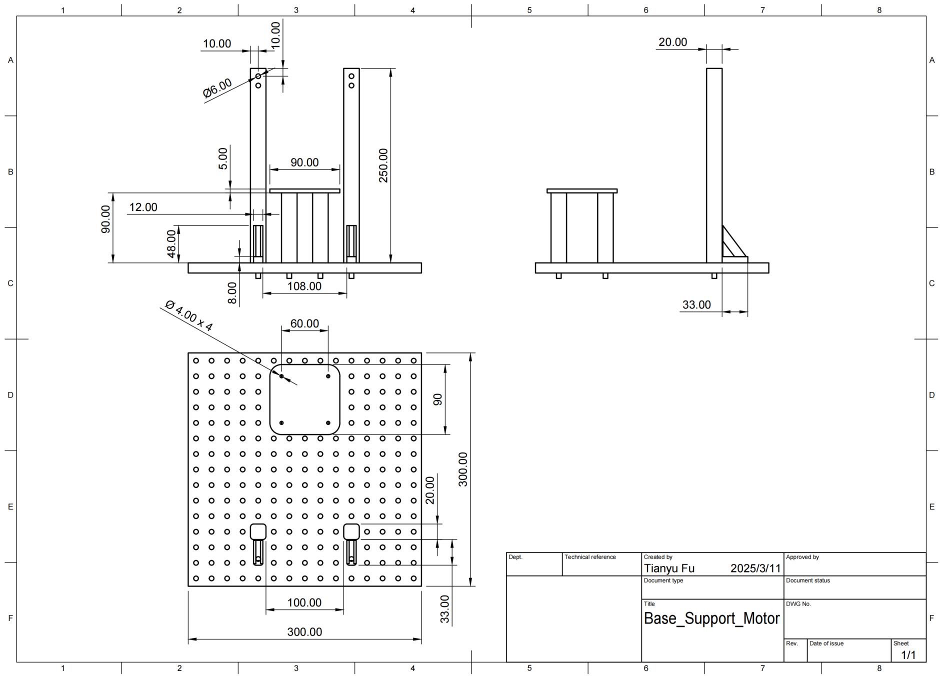


Figure 2.7: Orthographic Views of the Sample Stage and Supporting Part

2.2 Block Diagram

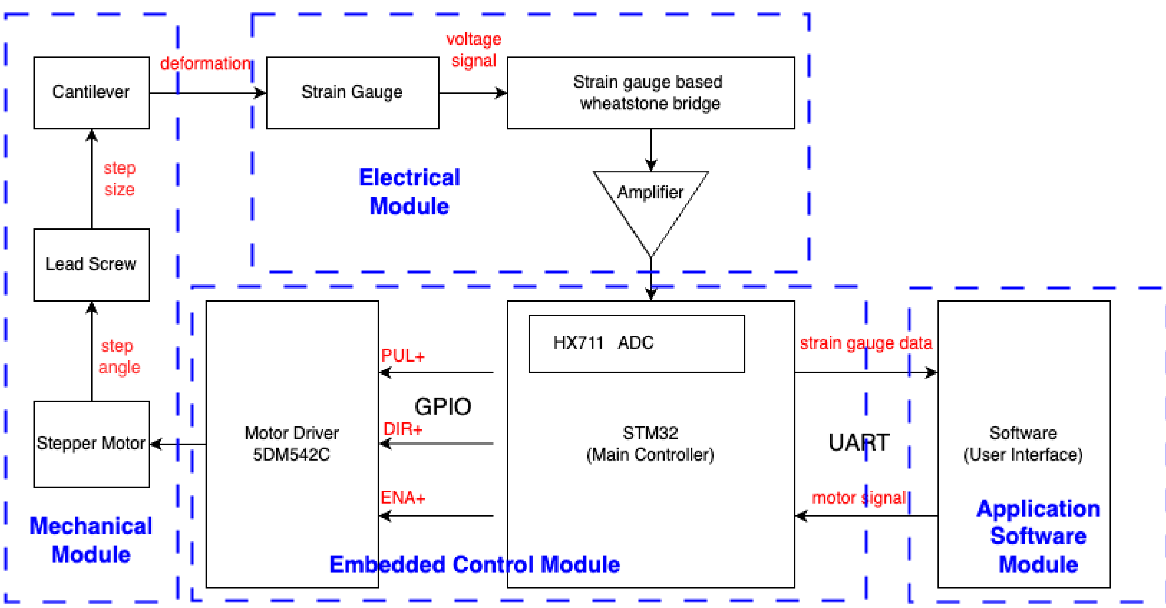


Figure 2.8: Block Diagram

2.3 Block Description

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

- **Functionality**: The stepper motor generates precise rotational motion, which is converted into linear displacement.
- **Requirements 1**: High-precision step control for accurate positioning.
- **Requirements 2**: Secure mounting with manual adjustment capability.
- **Requirements 3**: Stable electrical connection to the driver.

Lead Screw

- **Functionality**: Converts the rotational motion of the motor into linear displacement.
- **Requirements 1**: Minimal backlash for accurate positioning.
- **Requirements 2**: Strong coupling to prevent misalignment.

Cantilever

- **Functionality**: Applies force to the sample through its front-end sphere.
- **Requirements 1**: High rigidity with controlled flexibility.
- **Requirements 2**: precisely fabricated contact sphere.

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 Ω 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 Ω, 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)

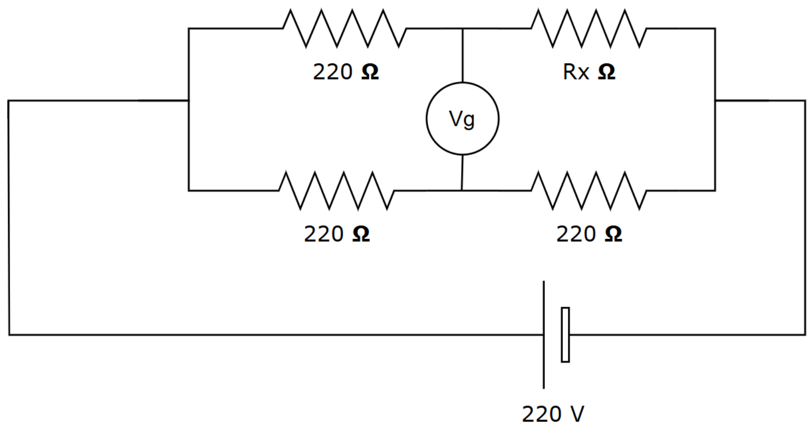


Figure 2.9: Schematic of the Wheatstone bridge

2.3.3 Embedded Control Module (STM32 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.

Communication Module: USART Communication between STM32 and Qt Software

- **Functionality:** The STM32 communicates with the upper-level software via UART, transmitting motor control signals and receiving strain gauge data.
- **Requirement 1:** The UART communication must ensure stable and low-latency data transfer.
- **Requirement 2:** The transmitted data must follow a structured format for seamless interpretation by the application software.

Motor Control Module: STM32 GPIO and Stepper Motor Driver

- **Functionality:** The STM32 interacts with the 5DM542C stepper motor driver using GPIO pins to send pulse, direction, and enable signals, allowing precise motor control. The pulse signal is generated using a timer.
- **Requirement 1:** The GPIO must generate accurate pulse sequences to control motor speed and direction with minimal delay.

- **Requirement 2:** The timer configuration must support fine-grained step control for precise displacement measurement.

Data Acquisition Module: Strain Gauge Signal Processing and ADC Conversion

- **Functionality:** The strain gauge's analog output is amplified and digitized using the HX711 ADC chip. The STM32 receives the digital signal through GPIO and transmits it to the application software.
- **Requirement 1:** The HX711 must provide high-resolution and low-noise digital conversion of the strain gauge signal.
- **Requirement 2:** The STM32 must handle real-time data acquisition and efficiently transmit the processed signal to the upper-level software.

2.3.4 Application Software Module (Qt Software Module)

The Application Software Module is responsible for sending control commands to STM32, processing acquired data, visualizing force-displacement curves, and storing measurement results.

Serial Communication Module: QSerialPort and STM32 UART Transmission

- **Functionality:** The Qt software communicates with STM32 via QSerialPort, sending motor control signals and receiving real-time sensor data.
- **Requirement 1:** The communication must support high-speed, bidirectional data exchange at a baud rate that matches the STM32's UART configuration.
- **Requirement 2:** The data format must be structured correctly to allow accurate command interpretation and real-time data visualization.

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

- **Functionality:** The system converts the strain gauge signal into force values and generates real-time force-displacement curves. A machine learning model is applied to analyze the curve and estimate the Young's modulus of the material.
- **Requirement 1:** The algorithm must efficiently convert strain gauge signals into force using calibrated transformation formulas.
- **Requirement 2:** The machine learning model must provide accurate Young's modulus estimations based on real-time measurement data.

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

- **Functionality:** The Qt-based graphical interface provides user-friendly controls for motor operation (start/stop, speed adjustment, directional control). It also displays real-time force-displacement curves and allows users to configure test parameters.
- **Requirement 1:** The GUI must be responsive and support real-time updates of measurement results.
- **Requirement 2:** The interface should allow intuitive interaction, enabling users to perform single or multiple test runs with minimal complexity.

2.4 Tolerance and Risk Analysis

2.4.1 Tolerance Analysis

Cantilever Design

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 2.1: 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].

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

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

The strain in the cantilever beam under the applied force (assumed to be 5N) is calculated as follows:

$$\epsilon = \frac{6FL}{Ewh^2} = \frac{6 \times 5 \times 0.05}{2.5 \times 10^9 \times 0.01 \times (0.003)^3} = 2222.2\ \mu\varepsilon$$

It is within the range of most commercially available strain gauges, $-2000 \sim 5000\ \mu\varepsilon$.

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 ±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.

Motor and Screw

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:

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

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 ±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.

After performing the tolerance analysis, we conclude that the system will meet the required performance criteria for achieving a step size of 0.2 µm and accurately measuring the mechanical properties of soft materials. The cumulative tolerances from individual components are within acceptable limits, and the overall system should function as intended.

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

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.