Temperature Compensation for Analogic Pressure Sensor

Erik Cura and Brendan Hon

FINAL REPORT

Table of Contents

Temperature Compensation for Analogic Pressure Sensor

Erik Cura and Brendan Hon

CONCEPT OF OPERATIONS

REVISION – Final
1 April 2024

Concept of Operations
for
Temperature Compensation for Analogic Pressure Sensor

Team CAPS

Approved by:

Erik Cura 4/27/2024
Project Leader Date

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Prof. Kalifatis Date

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Maccoy Merrell Date

Change Record

Rev.	Date	Originator	Approvals	Description
1	2/7/2024	Erik Cura, Brendan Hon		Draft Release
2	2/20/2024	Erik Cura, Brendan Hon		Updated Project Goal:403(Research/POC) and Subsystem Split
3	4/1/2024	Erik Cura, Brendan Hon		Final Revision

Table of Contents

List of Figures

1. Executive Summary

Taipro, the sponsor, has tasked us with the research, development, and analysis of an analog temperature compensation board for a piezoresistive pressure sensor following two separate strategies. Presently, the sensor lacks temperature compensation, requiring manual measurement of its resistance to select the appropriate calibration equation. The completed compensation board will convert the sensor's output voltage to a standardized value, enabling equation mapping irrespective of temperature fluctuations. This project will research and analyze both strategies in parallel to determine the optimal solution for the sponsor. The final solution will be adopted by Taipro and will eliminate extra actions taken by the customer, enhancing accuracy and efficiency in pressure measurements.

2. Introduction

The sensor in use is a piezoresistive MEMS pressure sensor. They are one of the most widely used sensors due to their ability to provide accurate and real-time measurements of pressure, their compact size, low power consumption, and cost-effectiveness. Additionally, their versatility allows for integration into diverse systems and applications, enhancing process efficiency, safety, and performance across industries. In practical applications, these silicon components are easily affected by temperature which has a significant impact on the sensor's accuracy, sensitivity, and linearity. This project will explore two strategies for eliminating these nonlinear characteristics by passing the output through our compensation board, which will remove the need for manual compensation on the user side.

2.1. Background

The project addresses a key limitation in current piezoresistive MEMS pressure sensors: their susceptibility to temperature fluctuations, which affects accuracy. Currently, users must manually adjust for temperature-induced nonlinear characteristics, increasing complexity, and potential errors. By introducing a temperature compensation board, this project aims to streamline pressure sensing by automatically adjusting sensor output voltage to a standardized value regardless of temperature variations. This will enhance accuracy, reliability, and user efficiency while broadening the sensors' various applications.

2.2. Overview

We will be exploring the development of two compensation systems that will address the challenge of accurately mapping pressure readings by accounting for temperature variations without adding unnecessary overhead. These separate solutions will be compared and analyzed based on cost, complexity, accuracy, and implementation feasibility. These solutions will utilize analog circuitry to modify the output or input voltage of the sensor to fit the compensation model. By implementing a robust compensation algorithm, we aim to ensure precise pressure measurements across a wide range of operating temperatures. The advantages of the final temperature compensation board include its simplicity, reliability, versatility, and cost-effectiveness. By eliminating the need for additional microcontrollers and temperature sensors, our solution offers a streamlined approach to temperature compensation, reducing complexity and minimizing hardware requirements.

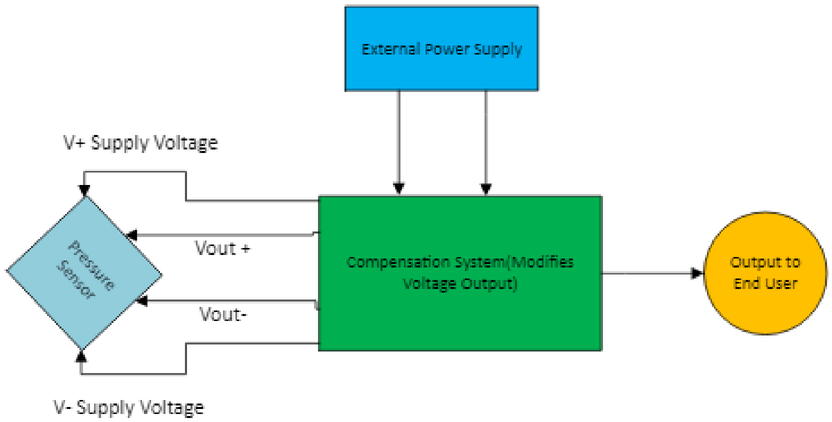

Figure 1: Compensation for an Analogic Pressure Sensor Diagram

2.3. Referenced Documents and Standards

[1] D. Xu and Y. Liu, "A temperature compensation algorithm of piezoresistive pressure sensor and software implementation," 2013 IEEE International Conference on Mechatronics and Automation, Takamatsu, Japan, 2013, pp. 1738-1742, doi: 10.1109/ICMA.2013.6618178.

[2] J. Long, "A Novel PWM Based Readout Circuit for Pressure Sensors," 2016 3rd International Conference on Information Science and Control Engineering (ICISCE), Beijing, China, 2016, pp. 779-783, doi: 10.1109/ICISCE.2016.171

[3] R. d. S. Pereira and C. A. Cima, "Thermal Compensation Method for Piezoresistive Pressure Transducer," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-7, 2021, Art no. 9510807, doi: 10.1109/TIM.2021.3092789.

3. Operating Concept

3.1. Scope

For the scope of this concept, two proof of concept systems will be fabricated. The boards will take in a voltage and perform the appropriate compensation for temperature. Through the sole use of analog circuitry, they will simplify the temperature compensation process, minimizing cost and hardware requirements. The exact deliverables for this project are as follows:

- Proof of concept boards following each strategy
- Designed test setup
- Calculation sheet for compensation of 1 sensor
- Calculation sheet of uncertainties
- Comparative analysis of the two compensation strategies

3.2. Operational Description and Constraints

The compensation system is intended for use by engineering and system integrators who are customers of Taipro. In reference to temperature, the pressure sensor will be in a harsh environment whereas the compensation board will be in a relatively nice environment where temperature is not extreme. To accomplish this the board must meet the following requirements:

- The output signal of the compensation system in the range of 0 to 150mV
- The input supply for the system is 5 V
- The size of the board is restricted to 100 mm by 150 mm
- The output of the system must be stable when the ambient temperature is 0°C to 40°C
- The system should not change the way that the user interacts with the pressure sensor. They should only use two wires to power the bridge and 2 wires for the output of the bridge
- The system should be developed in a purely analog fashion to minimize user complexity and cost
- Direct modification to the pressure sensor is not feasible
- Additional temperature sensors not desired

3.3. System Description

The Compensation for Analogic Pressure Sensor project will consist of two separate boards. Both boards will take input from the pressure sensor and will have one output to the user's data acquisition system. To design the boards the main components that need to be completed are as follows:

- **Development of the compensation algorithm:** The parameters important to the algorithm are the pressure, output voltage, supply voltage, and working temperature of the sensor. Data for these was obtained from calibration data where the output voltage was observed after applying known pressures at known temperatures. Once this data was obtained many mathematical models were tested to optimize accuracy.
- **Subsystem 1 - Analog Compensation Board:** The result of the model should be a system of equations. These equations will be implemented in an analog fashion on the board. The equations will be broken down into basic mathematical operations such as addition, subtraction, multiplication, division, and scaling. the appropriate combinations of op-amps, resistors, comparators, switches, and capacitors will be chosen to represent this.
- **Subsystem 2 - Passive Component Network Compensation Board:** For the second board we will be creating a separate method for compensation involving a number of resistors in different configurations to temper the offset and sensitivity effects of temperature.

3.4. Modes of Operations

Our temperature compensation systems will operate in a single mode. This mode will take in voltage input from MEMS(Micro-electro-mechanical systems) piezoelectric pressure sensor and process the signal to dampen the effects of temperature. A clean voltage signal will be outputted in real time to be converted into a pressure value downstream.

3.5. Users

Our temperature compensation systems will have a wide variety of applications in areas of turbulent temperature variation, or large temperature range. Notable usage of our systems will be used in industrial and manufacturing applications, where signals will have cascading effects on other systems. Other applications include military technologies and medical instrumentation. The system will offer high levels of accuracy and reliability, as well as maintain consistent readings despite temperature changes.

3.6. Support

Support will be provided in the form of our device manual, which will include information on the operations and installation of the device. The manual will also include specified data points and ranges needed to operate the device properly. Information about the hardware and schematics will also be provided.

4. Scenarios

4.1. High-Temperature Skews Pressure Reading

In certain applications, it is possible that temperatures do not remain at a constant level. Such variations in temperature will have a distinct impact on piezoresistive sensor readings. These readings could show pressure values higher than the true pressure at high temperatures. With the use of our temperature compensation system, the skewed signal caused by high heat will be compensated and processed to read the proper value.

4.2. Volatile Temperature Causes Signal Variations

In situations with heavy temperature variation, readings of pressure will also have variation at true constant pressure. This can cause issues when trying to pin down the correct pressure. The temperature compensation system addresses this issue by removing the extra noise caused by temperature variation, which will provide a steady pressure reading.

4.3. Malfunctioning Sensor

When signals are unreliable, it is difficult to identify the true cause of poor data readings. In cases where the sensor itself has succumbed to deterioration, signal unreliability due to malfunction may be attributed to other temperature variation, or take more time to troubleshoot. Our system can help streamline the troubleshooting process by providing reliable processed signals, which show sensor malfunction immediately.

5. Analysis

5.1. Summary of Proposed Improvements

- Simplicity in board design and signals
- Versatile and self-contained device
- Reliability and consistency
- Cost-effectiveness

5.2. Disadvantages and Limitations

- Dependance on sensor for input voltage signal
- Reliance on an initial model for behavior
- No control due to lack of digital interface and simplicity
- Modifications to the initial model will require physical change

5.3. Alternatives

Temperature compensation with a built-in temperature sensor

- Increases complexity with added sensor
- Complicates sensor portion
- May require close proximity to sensor
- Provides reliable temperature reference at all times

Microcontroller integration

- Expensive due to added microprocessor cost
- Decreases hardware need in device
- Digital interface creates ease of use

Temperature Compensation for Analogic Pressure Sensor

Erik Cura and Brendan Hon

Functional System Requirements

REVISION – Final
27 April 2024

Functional System Requirements

for

Temperature Compensation for Analogic Pressure Sensor

Prepared by:

Brendan Hon and Erik Cura 4/27/2024

Author Date

Approved by:

Erik Cura 4/27/2024

Project Leader Date

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Prof. Kalafatis Date

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Maccoy Merrell Date

Change Record

Rev.	Date	Originator	Approvals	Description
1	2/22/2024	Brendan Hon and Erik Cura		Revision 1
2	4/1/2024	Brendan Hon And Erik Cura		Final Revision

Table of Contents

List of Tables

List of Figures

1. Introduction

1.1. Purpose and Scope

One key limitation in current piezoresistive MEMS pressure sensing devices is their sensitivity to fluctuations in temperature. This is detrimental to the accuracy of the sensor and may cause the device to output data that reflects incorrect pressure. The technology currently used to address this problem involves manual adjustments to combat the nonlinear impacts of temperature. This process is not only complex but also creates the opportunity for more errors. With our proposal, compensation for temperature is integrated with the pressure device and automatically removes the effects of temperature. Our CAPS system will improve the accuracy and reliability of pressure sensor readings, as well as extend the applications of piezoresistive MEMS sensors.

To accomplish automatic temperature compensation, we will implement two possible solutions based on the same principle. Our CAPS board will be comprised of entirely analog components. This allows our board to adjust signals received from our pressure sensor in real time and output an accurate continuous signal, as well as avoid unnecessary overhead. In addition to the lack of a microcontroller, our board will not have any additional temperature sensors. This simplified design allows for sparse requirements and a single voltage output. With our two solutions, we can arrive at a versatile device that has minimal changes between different sensors.

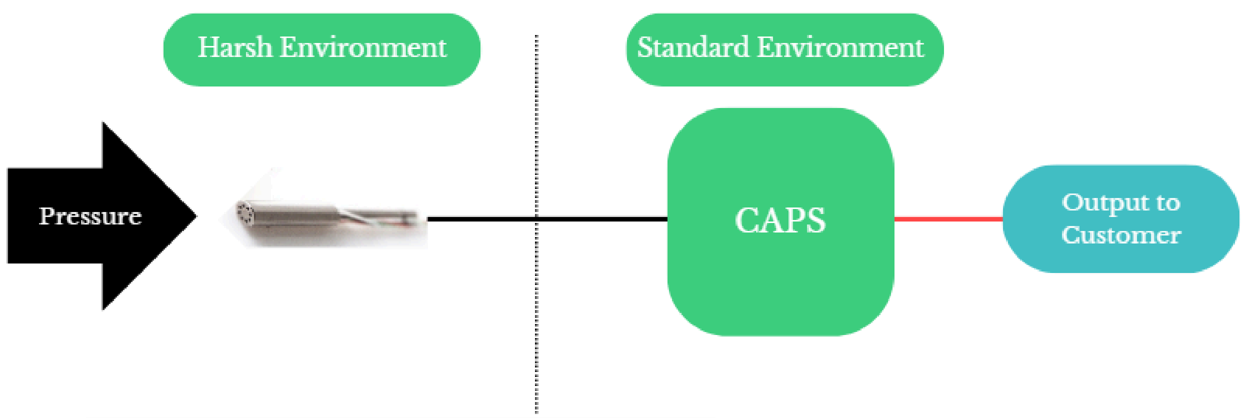

Figure 1. System Block Diagram

1.2. Responsibility and Change Authority

The team leader, Erik Cura, is responsible for making sure the requirements of our overall proposals are met. Modifications to aspects of our proposal will be confirmed with approval from our two sponsor representatives: Michel Saint-mard and Alexis Kozlowski.

Subsystem	Responsibility
Strategy #1: Analog Implementation of Regression	Erik Cura
Strategy #2: Passive Component Network	Brendan Hon

Table 1. Subsystem Responsibility Chart

2. Applicable and Reference Documents

2.1. Applicable Documents

The following documents, of the exact issue and revision shown, form a part of this specification to the extent specified herein:

Document Number	Revision/Release Date	Document Title
EN 50324-1	2002	Piezoelectric properties of ceramic materials and components
OP777_727_747-3131258	Revision D – 2011	OP727ARUZ Datasheet

Table 2. Applicable Documents

2.2. Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification and are not controlled by their reference herein.

Document Number	Revision/Release Date	Document Title
9510807	28 June 2021	Thermal Compensation Method for Piezoresistive Pressure Transducer
114119	27 August 2023	Design and implementation of a kind of high precision temperature compensating system for silicon-on-sapphire pressure sensor

Table 3. Reference Documents

2.3. Order of Precedence

Information regarding drawings, specifications, standards, and documents described in this text takes precedence over other documents. Documents used within this text are purely for reference and do not supersede this text.

3. Requirements

3.1. System Definition

The Temperature Compensation for Analogic Pressure Sensor System is the compensation for the non-linear output of a piezoresistive sensor at varying temperatures. It allows users to read the output voltage directly from the board without having to perform manual compensation techniques. The uncompensated output voltage of the pressure sensor will feed into the CAPS board. The output of the CAPS board will be a scaled voltage which can be used to calculate the pressure with a given calibration sheet. The Temperature Compensation for Analogic Pressure Sensor has two subsystems which are two separate strategies for achieving this compensation. The first subsystem is Analog Implementation of Regression and the second subsystem is Passive Component Network Compensation.

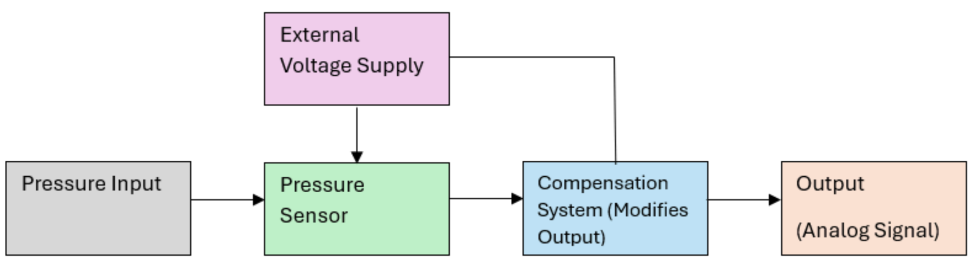

Figure 2. Block Diagram of System 1

3.1.1 Analog Implementation of Regression

3.1.1.1 Compensation Model
The calibration data of the sensor is analyzed using statistical and machine learning methods to produce a compensation model that is targeted at modifying the output voltage of the pressure sensor.

3.1.1.2 Analog Implementation
The produced model will be implemented in an analog fashion on the board. This strategy modifies the output of the pressure sensor by feeding it through a series of resistors, amplifiers, and comparators.

3.1.1.3 Calibration Equation
A calibration equation is made that correctly maps the output voltage of the board to the correct pressure.

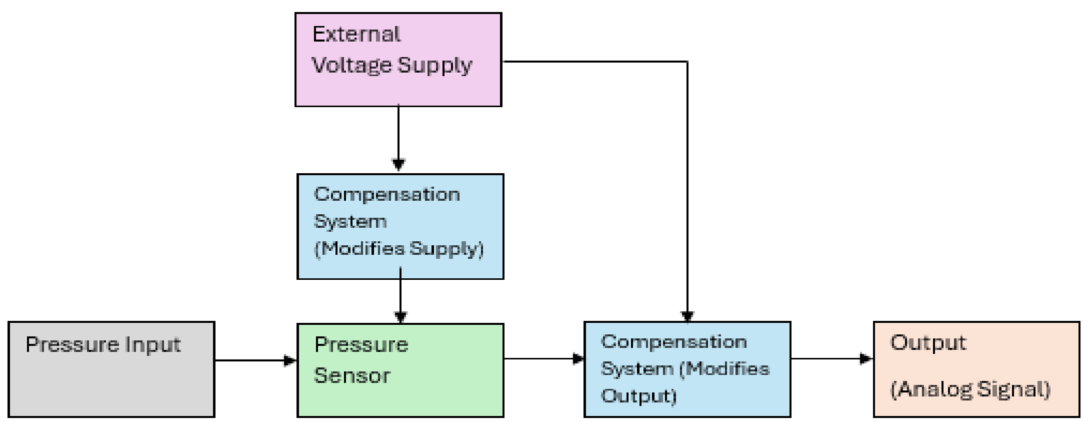

Figure 3. Block Diagram of System 2

3.1.2. Passive Component Network

3.1.2.1. Piezoelectric Sensor Model
A model is created to simulate the behavior of a true piezoelectric pressure sensor and its branches. This will allow us to create different kinds of sensors for testing, as well as format the correct design to meet certain sensor specific needs.

3.1.2.2. Network Design and Implementation
The optimal components must be selected to fit the specific sensor, and a configuration must be decided to best serve the purpose of compensation.

3.2. Characteristics

3.2.1. Functional / Performance Requirements

3.2.1.1. Accuracy

The percent error at 1 sigma of the final calculated pressure shall be less than 2 percent.

> *Rationale: This is a core system performance requirement. The percent error must be this low to allow for accurate computation of the pressure by the user.*

3.2.1.2. Operating Temperature

The CAPS system shall operate at temperatures up to 80°C and shall have steady output voltage from 0°C to 40°C.

> *Rationale: This is a requirement specified by our customer to operate consistently at the desired temperature range.*

3.2.2. Physical Characteristics

3.2.2.1. Board Dimensions

The size of the CAPS board shall not exceed 100 mm x 150 mm.

> *Rationale: This is a requirement specified by our customer due to the constraints of their system.*

3.2.2.2. Mounting

Our proposed systems will be connected to the customer’s device and MEMS pressure sensor from our sponsor. A single wire connection will feed a voltage signal to the customer, as well as connect the CAPS board to the sensor.

> *Rationale: Our sponsor seeks a simple device that requires minimal changes and wiring to integrate into the overall system.*

3.2.3. Electrical Characteristics

3.2.3.1. Inputs

The signal entering the CAPS system shall be 0mV to 150mV. The CAPS system shall not be damaged with any absence or combination of input signals in accordance with ICD specifications.

> *Rationale: By design, should limit the chance of damage or malfunction by user/technician error.*

3.2.3.1.1 Power Consumption

The maximum peak power of the system shall not exceed 5 watts.

> *Rationale: This is a requirement specified by our sponsor for generic usage across different applications.*

3.2.3.1.2 Input Voltage Level

The input voltage supply level for both the CAPS system and sensor shall be regulated at +-5V DC

Rationale: Requirement specified by the sponsor due to pressure sensor specifications.

3.2.3.2. Outputs

3.2.3.2.1 Data Output

The Temperature CAPS System shall output a voltage between 0 mV to 150mV

Rationale: Requirement specified by the sponsor due to pressure sensor specifications.

3.2.3.2.2 Calibration Equation

The Temperature CAPS System shall include a calibration document containing the final compensation equation to match the output voltage of the CAPS system to the correct pressure.

Rationale: Enables the user to obtain the correct pressure based on the output of the CAPS board.

3.2.4. Environmental Requirements

3.2.4.1. Temperature

The output of the system must be stable when the ambient temperature is 0°C to 40°C. The system shall be protected and operable in temperatures of up to 80°C,

Rationale: This is a requirement specified by our sponsor to suit the desired applications.

3.2.4.2. External Contamination

The CAPS board shall be sealed and protected from external contamination that may arise during the usage of the device.

Rationale: Protects the system from errors that may occur from contamination of electrical equipment.

4. Support Requirements

Customers that use our CAPS board will require a separate system capable of connecting to the board and executing the equation that we offer to convert voltage value into a pressure value, as well as a functioning MEMS pressure sensor created by Taipro, our sponsor. The system will come with a manual, which will list specifications for operation and maintenance. We will also be providing the equation to convert our compensated voltage into a usable pressure reading.

Appendix A: Acronyms and Abbreviations

mV	Millivolt
mm	Millimeter
VDC	Voltage Direct Current
ICD	Interface Control Document
C	Celcius
V	Volt
CAPS	Compensation for Analogic Pressure Sensor
MEMS	Micro-electromechanical systems

Temperature Compensation for Analogic Pressure Sensor

Erik Cura and Brendan Hon

INTERFACE CONTROL DOCUMENT

REVISION – Final
22 April 2024

INTERFACE CONTROL DOCUMENT
FOR
Temperature Compensation for Analogic Pressure Sensor

PREPARED BY:

Erik Cura 4/27/2024
Author Date

APPROVED BY:

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Project Leader Date

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Prof. Kalafatis. Date

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Maccoy Merrell Date

Change Record

Rev.	Date	Originator	Approvals	Description
1	2/12/2024	Erik Cura and Brendan Hon		Draft Release
2	4/1/2024	Erik Cura and Brendan Hon		Final Revision

Table of Contents

List of Tables

1. Overview

This document is provided to detail how both compensation strategies will interface with the end user and pressure sensor. It will list all possible inputs, and outputs, and how each system will manage each. An explanation of inputs to the CAPS board from the pressure sensor and how that signal is conditioned will be detailed.

2. References and Definitions

2.1. References

Refer to section 2.2 of the Functional System Requirements document.

2.2. Definitions

CAPS	Compensation for an Analogic Pressure Sensor
mA	Milliamp
mW	Milliwatt
mV	Millivolt

3. Physical Interface

3.1. Weight

3.1.1. Strategy #1: Analog Implementation of Regression

Component	Weight	Number of Item
Opamp(OP727ARUZ)	0.001157 oz	4
Instrumentation Amplifier(INA819IDR)	0.002991 oz	3
Analog Comparator(TLV3501AIDBVT)	0.001270 oz	1
Analog 2:1 Mux(ADG819BRTZ-REEL7)	0.001270 oz	1
Resistor(RMCF0603FT23K2)	0.000071 oz	2
Resistor(CRCW0603200RFKEA)	0.000071 oz	2
Resistor(CRCW0603130RFKEA)	0.000071 oz	2
Resistor(RT0603FRE0710KL)	0.000071 oz	10
Resistor(MCT06030D4701BP100)	0.000071 oz	2

Resistor(TNPW04021K20BYEP)	0.000071 oz	3
Resistor(CRCW080530R0FKEA)	0.000071 oz	2
Resistor(RP73PF1E11R3BTDF)	0.000071 oz	2
Resistor(CRCW060310R0FKEA)	0.000071 oz	2
Resistor(CRCW040220R0FKED)	0.000071 oz	2
Resistor(CRCW04021K00FKED)	0.000071 oz	2
Resistor(CRCW0402160RFKED)	0.000071 oz	2

Table 1: Strategy #1 Weight

3.1.2. Strategy #2: Passive Component Compensation

Component	Weight	Number of Item
Resistor(RT0603FRE0710KL)	0.000071 oz	2
Resistor(CRMA1206AF500KFKEF$)	0.000550 oz	1
Resistor(HVCB2512FDD60K0)	Unlisted	1
Connection Header(M50-3600542)	0.002469 oz	1

Table 2: Strategy #2 Weight

3.2. Dimensions

3.2.1. Dimension of Strategy #1 Subsystem

Component	Length	Width	Height
Opamp(OP727ARUZ)	3 mm	4.4 mm	1.05 mm
Instrumentation Amplifier(INA819IDR)	4.90 mm	3.91 mm	1.35 mm
Analog Comparator(TLV3501AIDBVT)	2.9 mm	1.6 mm	1.15 mm
Analog 2:1 Mux(ADG819BRTZ-REEL7)	2.9 mm	1.6 mm	1.15 mm
Resistor(RMCF0603FT23K2)	1.6 mm	0.8 mm	0.45 mm

Resistor(CRCW0603200RFKEA)	**1.6 mm**	**0.8 mm**	**0.45 mm**
Resistor(CRCW0603130RFKEA)	**1.6 mm**	**0.8 mm**	**0.45 mm**
Resistor(RT0603FRE0710KL)	**1.6 mm**	**0.8 mm**	**0.45 mm**
Resistor(MCT06030D4701BP100)	**1.6 mm**	**0.8 mm**	**0.45 mm**
Resistor(TNPW04021K20BYEP)	**1 mm**	**0.5 mm**	**0.3 mm**
Resistor(CRCW080530R0FKEA)	**2 mm**	**1.25 mm**	**0.45 mm**
Resistor(RP73PF1E11R3BTDF)	**1 mm**	**0.5 mm**	**0.3 mm**
Resistor(CRCW060310R0FKEA)	**1.6 mm**	**0.8 mm**	**0.45 mm**
Resistor(CRCW040220R0FKED)	**1 mm**	**0.5 mm**	**0.3 mm**
Resistor(CRCW04021K00FKED)	**1 mm**	**0.5 mm**	**0.3 mm**
Resistor(CRCW0402160RFKED)	**1 mm**	**0.5 mm**	**0.3 mm**

Table 3: Strategy #1 Dimensions

3.2.2. Dimension of Strategy #2 Subsystem

Component	**Length**	**Width**	**Height**
Resistor(RT0603FRE0710KL)	**1.6 mm**	**0.8 mm**	**0.45 mm**
Resistor(CRMA1206AF500KFKEF$)	**3.18 mm**	**1.6 mm**	**0.64 mm**
Resistor(HVCB2512FDD60K0)	**6.35 mm**	**3.18 mm**	**0.76 mm**
Connection Header(M50-3600542)	**6.35 mm**	**5.5 mm**	**4.68 mm**

Table 4: Strategy #2 Dimensions

4. Electrical Interface

4.1. Primary Input Power

4.1.1. CAPS Board

The CAPS board will be powered by a regulated DC power supply at +5V and -5V

4.2. Voltage and Current Levels

4.2.1. Average Consumption

Component	Voltage(V)	Current(uA)	Power (mW)
Opamp(OP727ARUZ)	5	320	75
Customer MEMS Pressure Sensor	2.5-6.0 V	500	50

Table 5: Average Voltage and Current Levels

4.3. Signal Interfaces

For Subsystem 1: Analog Regression the following inputs must be provided to the compensation system to ensure correct usage.

4.3.1. Output Voltage of Pressure Sensor

The input for the output voltage terminals should come from the two output wires of the pressure sensor. The top input terminal should receive the V- input and the bottom terminal should receive the V+ terminal.

4.3.2. Supply Voltage of the Pressure Sensor

This is the voltage across the two power supply terminals. The top input terminal should receive V+ input and the bottom input terminal should receive the V- input.

4.3.3. Series Resistor Voltage Input

This is the voltage across the 100-ohm resistor in series with the pressure sensor. This voltage determines which piecewise compensation equation to use. The top input terminal should receive V+ input and the bottom input terminal should receive the V- input.

For Subsystem 2: Passive Component Network the following inputs must be provided to the compensation system to ensure correct usage.

4.3.4. Supply Voltage Input

The board requires a supply voltage V+ to be supplied to the input pin connected to Rs1 and a V- connected to the bottom pin connected to Rs2.

4.3.5. Voltage Output

Output can be read directly from the terminals of the sensor.

Temperature Compensation for Analogic Pressure Sensor

Erik Cura and Brendan Hon

SCHEDULE AND VALIDATION

REVISION – Final

Work Schedule

Work	End Date	Owner	Status	Completion Date
Literature Review and Research	2/8/2024	All	Completed	2/8/2024
Potential Solution Development	2/14/2024	All	Completed	2/14/2024
1st Solution Proposal	2/15/2024	All	Completed	2/15/2024
Concept of Operations	2/24/2024	All	Completed	2/24/2024
Functional System Requirements	2/24/2024	All	Completed	2/24/2024
Interface Control Document	2/24/2024	All	Completed	2/24/2024
Midterm Presentation	2/26/2024	All	Completed	2/26/2024
Strategy #2: Strategy Analysis	3/4/2024	Brendan	Completed	3/4/2024
Strategy #2: Revised Circuit Equation	3/7/2024	Brendan	Completed	3/7/2024
Strategy #1: Piecewise Regression Calculation	3/9/2024	Erik	Completed	3/9/2024
Strategy #1: Circuit Design and Simulation	3/15/2024	Erik	Completed	3/15/2024
Strategy #2: Preliminary Circuit Design	3/15/2024	Brendan	Completed	3/15/2024
Strategy #2: Simulation Design	3/22/2024	Brendan	Completed	3/22/2024
Strategy #1: PCB Schematic Design	3/25/2024	Erik	Completed	3/25/2024

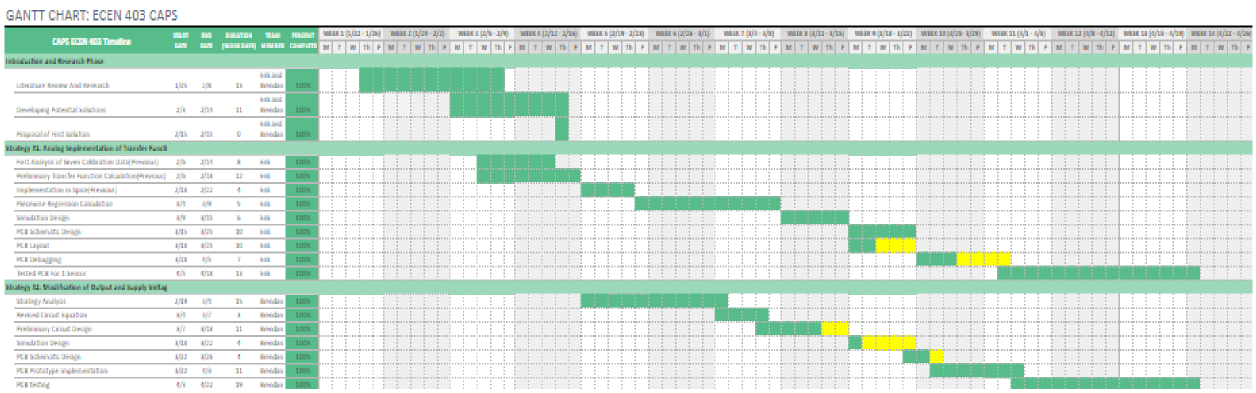
Strategy #1: PCB Layout	**3/25/2024**	**Erik**	**Completed**	**3/25/2024**
Strategy #2: PCB Schematic Design	**3/26/2024**	**Brendan**	**Completed**	**3/26/2024**
Strategy #2: PCB Prototype Implementation	**4/3/2024**	**Brendan**	**Completed**	**4/3/2024**
Strategy #1: PCB Debugging	**4/5/2024**	**Erik**	**Completed**	**4/5/2024**
Final Presentation	**4/8/2024**	**All**	**Completed**	**4/8/2024**
Strategy #1: Completed and Tested PCB	**4/18/2024**	**Erik**	**Completed**	**4/18/2024**
Strategy #2: PCB Testing	**4/18/2024**	**Brendan**	**Completed**	**4/18/2024**
Final Demo	**4/22/2024**	**All**	**Completed**	**4/22/2024**
Finish Final Report	**4/25/2024**	**All**	**Completed**	**4/25/2024**
Final Report	**4/27/2024**	**All**	**Completed**	**4/27/2024**

Validation Schedule

Task	Specification	Validation	Result	Owner
1. Instrumentation Amplifier	Ensure accurate and reliable voltage is supplied into amplifiers for compensation	Use of a multimeter and oscilloscope to ensure the correct value	Pass	Erik
2. Segment Selection	Correct selection input is triggered given a differential series resistance voltage	Use of analog comparator to generate selection bit	Pass	Erik
3. Output Selection	Correct segment output is chosen given specific inputs	Use of an analog switch to select the correct output	Pass	Erik
4. Intermediate Value Verification	Value from the first series amplifier models correct value	Multimeter and oscilloscope to ensure the correct value	Pass	Erik
5. Output Accuracy	The percent error falls under 1.5%	Analyze and compare output to expected results	Mixed Results	Erik

5. Output Signal Limit	Verify useful output voltage in desired range	Verification with multimeter and graphing	Fail	Brendan
6. Prediction Accuracy	Verify accuracy of output accuracy to be less than 3%	Verification with multimeter and graphing	Fail	Brendan
7. Resistance Operating Rande	Board to remain functional for 6000 to 9000 ohms	Verification with multimeter and graphing	Passed	Brendan

Gantt Chart:



Key: Green means completed on schedule and Yellow means completed late

Schedule and Validation Analysis:

Initially, we were on top of our schedule specified in the execution plan, however, our project definition/ requirements changed several times due to rejected solution proposals and misunderstandings between the sponsor and our team. This set us behind as all the work we did for our initial solution was essentially nullified. After essentially starting over we updated our execution plans to fit our solution strategy. From this point, we were able to hit all specified deadlines with the exception of shipping delays.

Temperature Compensation for Analogic Pressure Sensor

Erik Cura and Brendan Hon

SUBSYSTEM REPORTS

REVISION – Final
22 April 2024

Subsystems Report

for

Temperature Compensation for Analogic Pressure Sensor

Prepared by:

____
Author **Date**

Approved by:

Erik Cura 4/22/2024
Project Leader **Date**

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Prof. Kalafatis **Date**

____
Maccoy Merrell **Date**

Change Record

Rev.	Date	Originator	Approvals	Description
1	4/22/2024	Erik Curaand Brendan Hon		Original Release

Table of Contents

List of Tables

List of Figures

1. Introduction

In order to successfully develop two separate thermal compensation systems as per the requirements of Taipro, we broke up the request into two separate subsystems with each subsystem being its own compensation system following a different compensation method. These subsystems are:

1. Compensation system via Analog Regression Implementation
2. Compensation system via passive resistor network

The detailed operation and validation of these subsystems will be elaborated on in the following pages.

2. Analog Regression Implementation Subsystem Report

2.1. Subsystem Introduction

This Subsystem implements temperature compensation using a series of precision analog circuits to implement a real-time compensation model, which corrects for both linear and non-linear temperature effects on the sensor output. This subsystem was tested to confirm its stability, capacity, and consistency. Each test helped verify that it performs the required compensation. For prototyping and demonstration purposes, the lab instruments will be used to simulate the outputs of the sensor.

Model	Supply Voltage Order	Output Voltage Order
1. P= β0 + β1 * Vout	1	0
2. P= β0 + β1 * Vout+ β2 *Vsupply	1	1
3. P= β0 + β1 * Vout+ β2 *Vsupply +β3*Vout^2 +β3*Vout*Vsupply	2	1
4. P= β0 + β1 * Vout+ β2 *Vsupply +β3*Vsupply^2 +β3*Vout*Vsupply	2	2
5. P= β0 + β1 * Vout^2+ β2 *Vsupply^2	2	2

Table 2.1 Table of Proposed Mathematical Models

2.2. Subsystem Details

The primary challenge with this subsystem was the selection of the compensation method. Many ideas were proposed such as a microcontroller-based compensation system and a temperature sensor-based compensation system but these ideas were not selected due to additional unwanted complexities. The final idea selected was the strict use of only analog components due to latency, inherent reliability, and compatibility with the existing sensor framework. Specifically, the model is a piecewise regression model with two segments that are selected based on the differential voltage of the series resistor. The models analyzed are shown in Figure 2.1 where Vout is the differential output voltage of the bridge Vsupply is the supply voltage of the pressure sensor. All models were analyzed to determine which most efficiently described the variations. The choice of the final model took into account not only the prediction accuracy but the hardware implementation complexity and cost. After taking into consideration these factors model 2 was chosen.

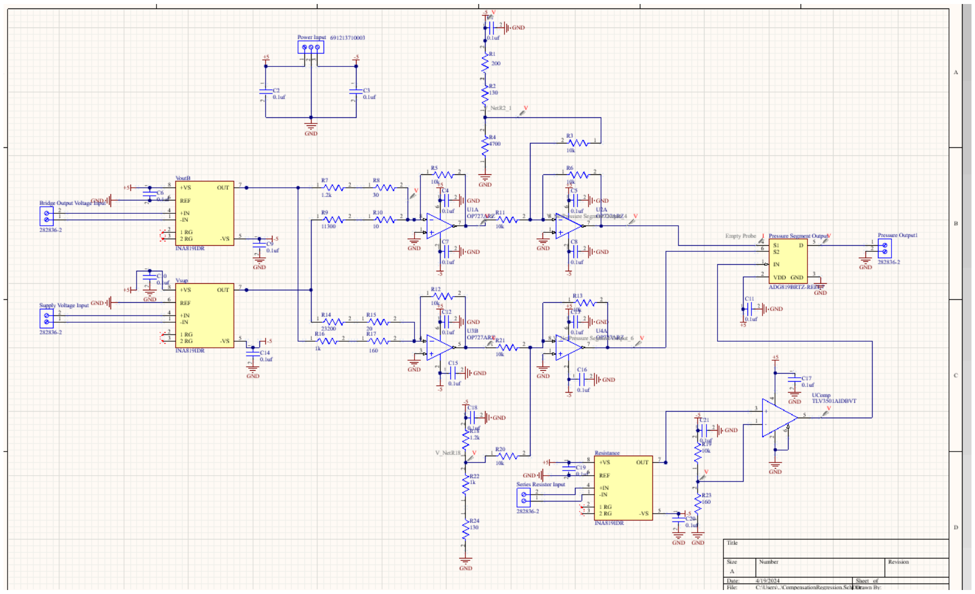

Figure 2.1 Schematic of the Compensation System

The first part of this subsystem is the input terminals of Bridge Output Voltage, Supply Voltage Input, and Series Resistance input. The Bridge Output Voltage terminal must receive the Vout - output in the top slot and the Vout+ terminal in the bottom slot. The Supply Voltage Input must receive the differential voltage across the pressure sensor as a whole with the top terminal receiving the voltage along the Vsup+ input and the bottom terminal receiving the voltage along the Vsup- input. The Series Resistance input should receive the differential voltage across the 100-ohm resistor in series with the pressure sensor. These differential inputs are fed into the INA819IDR instrumentation amplifier which will produce the desired voltage output. The main compensation for the system can be broken up into two segments each representing the compensation equation from the generated piecewise function. In each segment, two OP727ARUZ opamps perform the appropriate voltage modifications. The first amplifier performs the function of a Summing Amplifier combining the β1 * Vout+ β2 *Vsupply terms. The second amplifier adds the offset given by β0. The voltage offset is given by a voltage divider between the -5V input and ground. The next critical portion of this subsystem is the output selection logic. The final output value is selected from the proper segment using the ADG819BRTZ-REEL7 analog switch whose selection input is the result of the TLV3501AIDBVT analog comparator. This comparator compares the differential voltage across the series resistor and a set voltage divider value which models the piecewise function criteria.

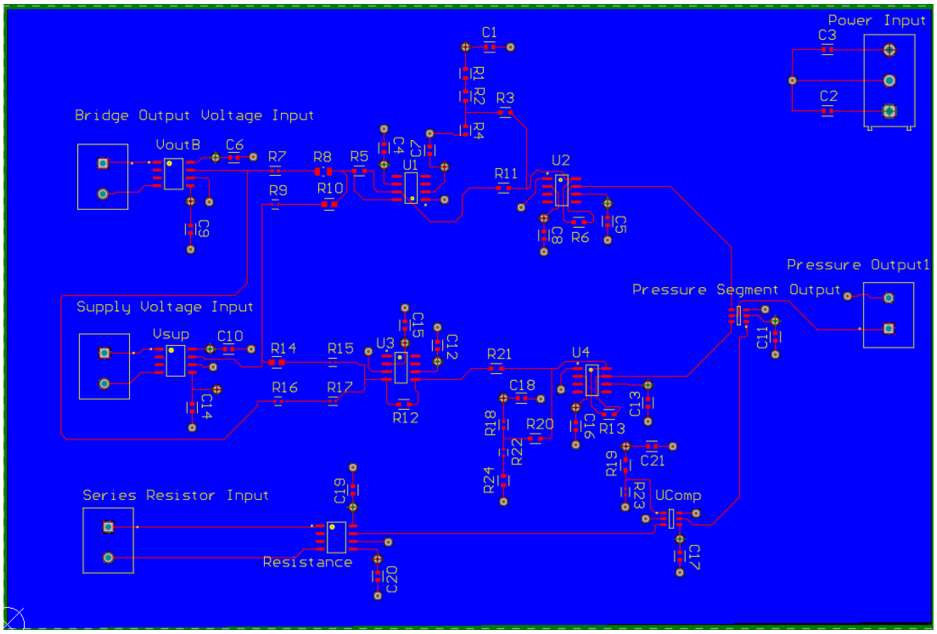

Figure 2.2 Fully Designed Board Altium 2D View

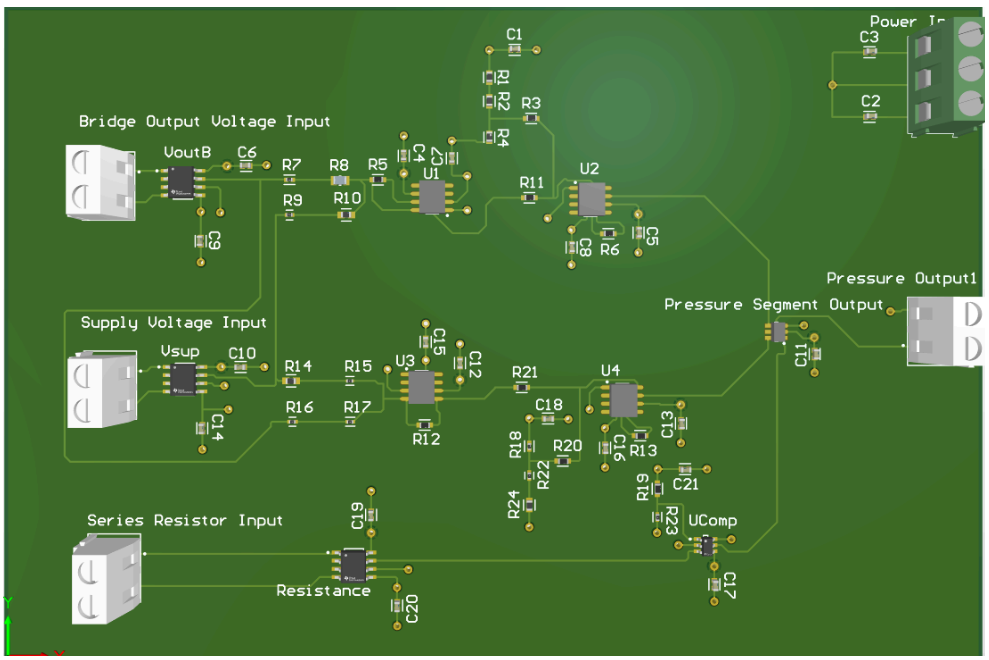

Figure 2.3 Fully Designed Board Altium 3D View

Once the schematic and SPICE simulations were completed I moved to designing the board. Due to the number of components that needed both a +5 V power supply and a -5 V power supply, I opted for a 4-layer board where the inner layers were set as power planes and the bottom layer was designated as ground. Once the design was fully routed and verified it was ordered from JLCPCB. After receiving the board the components were soldered on and verification could begin.

2.3. Subsystem Validation and Results

The figure above shows the full PCB with all the components soldered for the Analog regression implementation. After all soldering issues were identified and fixed, artificial stimulus could be supplied to the board to observe the output. To efficiently and accurately test the board I wrote Python scripts to directly communicate with the lab instruments to supply inputs as well as logging the measurement outputs. This program automatically takes the logged data performs analysis and generates visualizations. This iterative validation process and tests are shown in the table below.

Task	Specification	Validation	Result
1. Instrumentation Amplifier	Ensure accurate and reliable voltage is supplied into amplifiers for compensation	Use of a multimeter and oscilloscope to ensure the correct value	Pass
2. Segment Selection	Correct selection input is triggered given a differential series resistance voltage	Use of analog comparator to generate selection bit	Pass
3. Output Selection	Correct segment output is chosen given specific inputs	Use of an analog switch to select the correct output	Pass
4. Intermediate Value Verification	Value from the first series amplifier models correct value	Multimeter and oscilloscope to ensure the correct value	Pass
5. Output Accuracy	The percent error falls under 1.5%	Analyze and compare output to expected results	Mixed Results

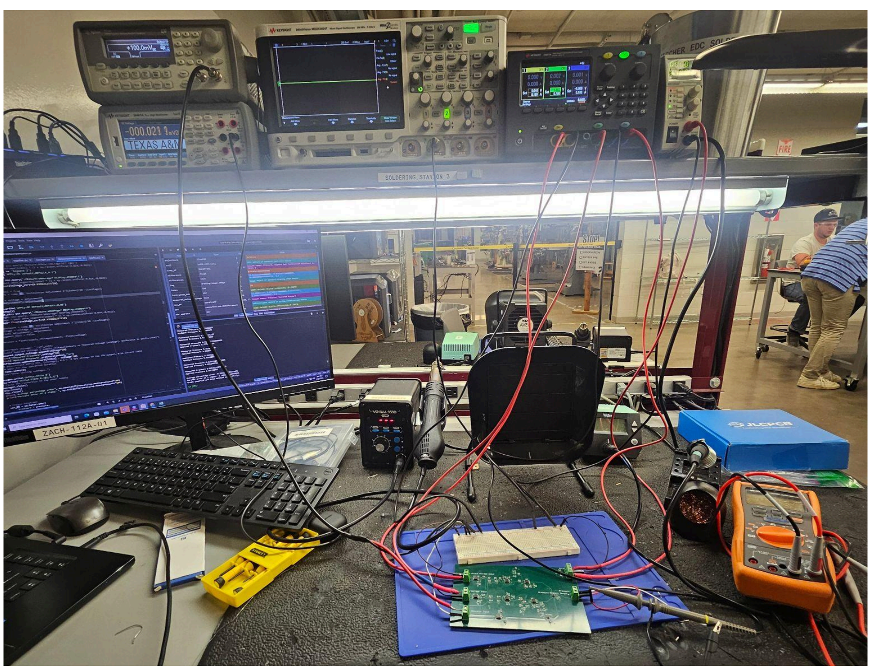

Figure 2.4 Board Attached to Test Setup

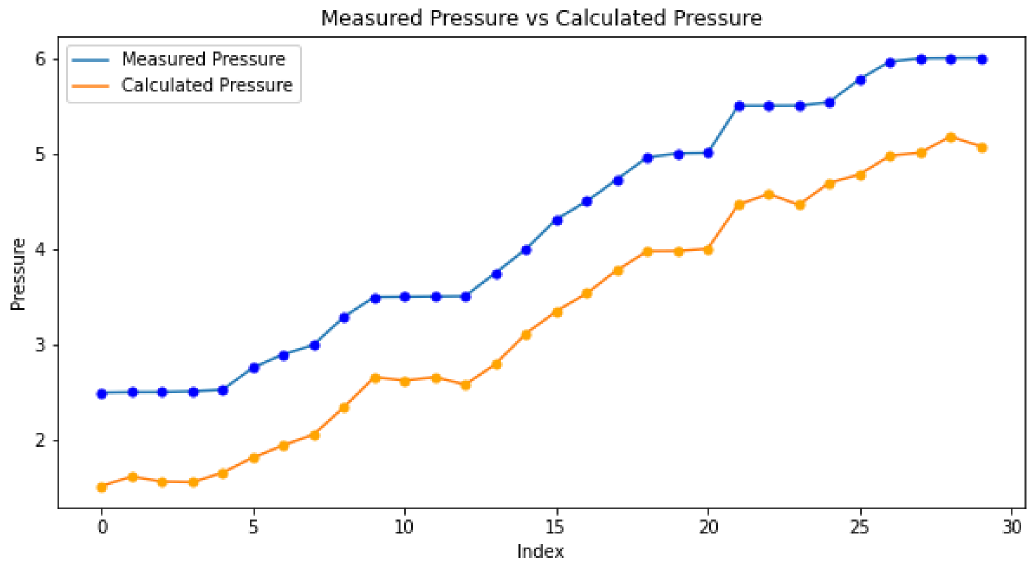

Figure 2.5 Results Graph Given Input Stimulus

The reason for the mixed results label for the validation of the accuracy is as follows. After running the testing scripts and performing the analysis the above results were generated. Upon inspection of the graph, it can be seen that the output of the system(Calculated Pressure) follows the correct trend of the actual pressure value but is offset on the y-axis. The difference, however, is systematic and predictable. This offset is almost constant at 0.94. Once this offset is applied to the data the following results can be observed.

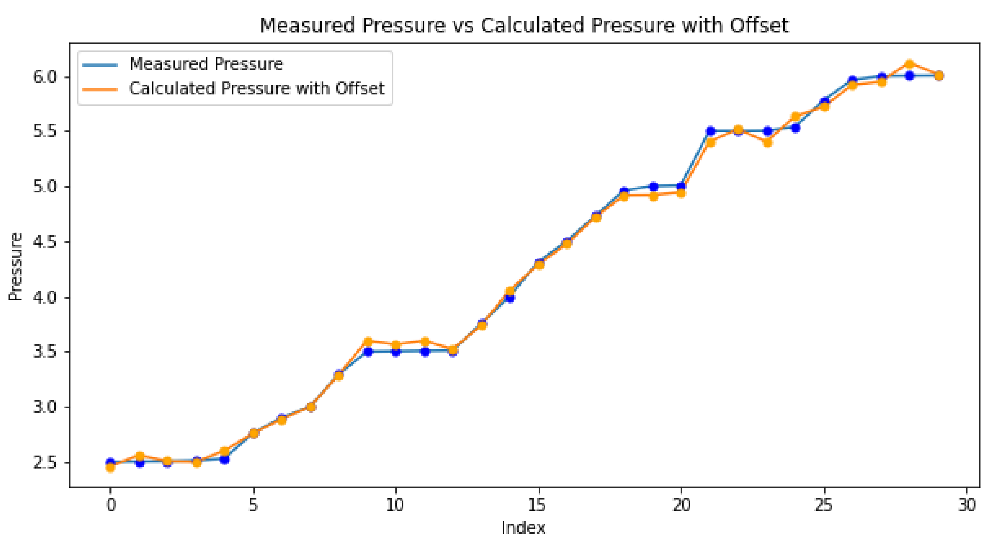

Figure 2.6 Results Graph Given Input Stimulus with Offset

With the given offset the prediction accuracy follows the real value almost perfectly with an average error of ~1%. After further analysis this constant offset results from the drop in voltage cascading from component to component as well as the drop from the oscilloscope measurement.

2.4. Conclusion and Failure Analysis

The Analog Regression Implementation Subsystem has successfully demonstrated its capability for real-time compensation of temperature effects on sensor outputs through a series of analog circuits. The system was tested to assure stability and accuracy, showing promise in its operational consistency. Model selection was critical, balancing prediction accuracy with hardware simplicity and cost-effectiveness, leading to the arrival at a piecewise regression approach. Post-assembly testing of the final board design revealed a predictable offset in the output, which, once accounted for, yielded a high accuracy rate with an average error of approximately 1%. In the future, the voltage drop offsets could be accounted for using components with higher precision specifications or additional offset circuitry. Additionally, many optimizations could be made such as resistor selection and space usage on the board.

3. Passive Component Network Subsystem Report

3.1. Subsystem Introduction

The passive resistor network employs the use of passive components only to mitigate the effects of temperature on the sensor. This method primarily focuses on reducing the change caused by temperature rather than actively correcting the output signal. The simple layout and low number of components provide a solution that is both cheap and ideally easily interchangeable between sensors.

3.2. Details

The passive component method addresses two key attributes of the effect of temperature in piezoresistive pressure sensors:

- Temperature effect on output voltage offset
- Temperature effect on pressure sensor sensitivity

Both these attributes are linearly correlated with temperature as shown below. This behavior is observed consistently in piezoresistive sensor calibration data.

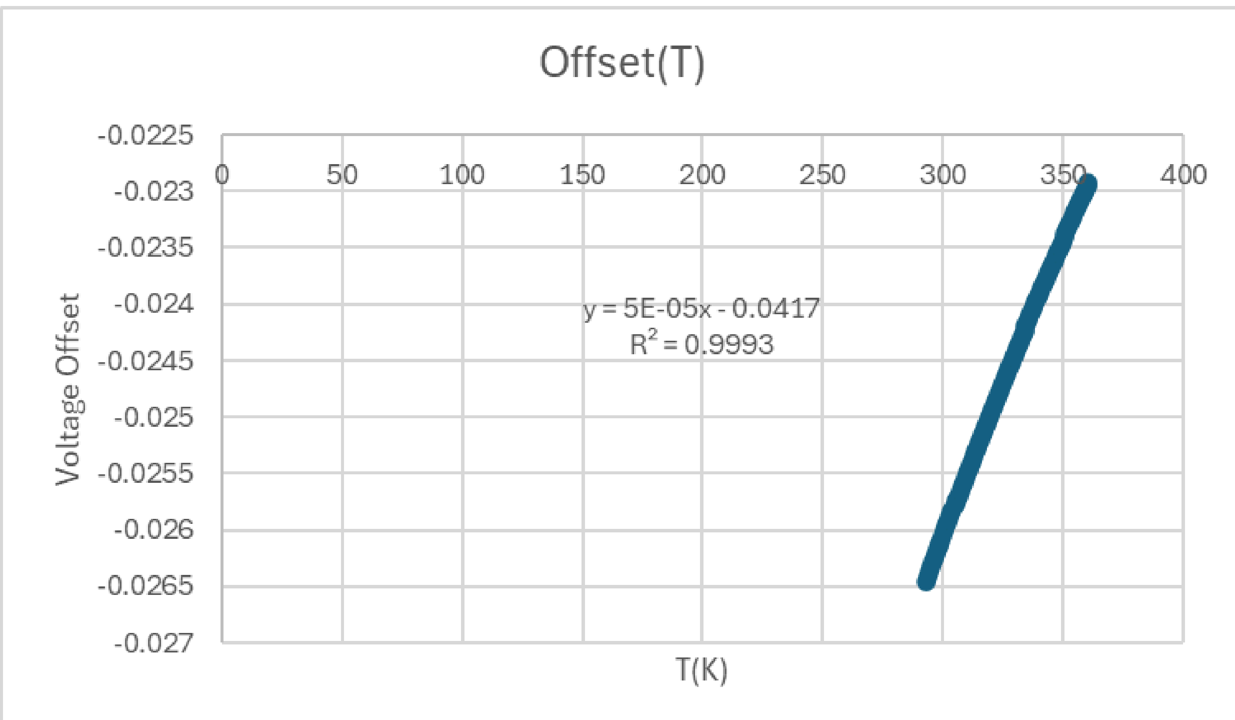

Figure 3.1 Voltage Offset vs. Temperature

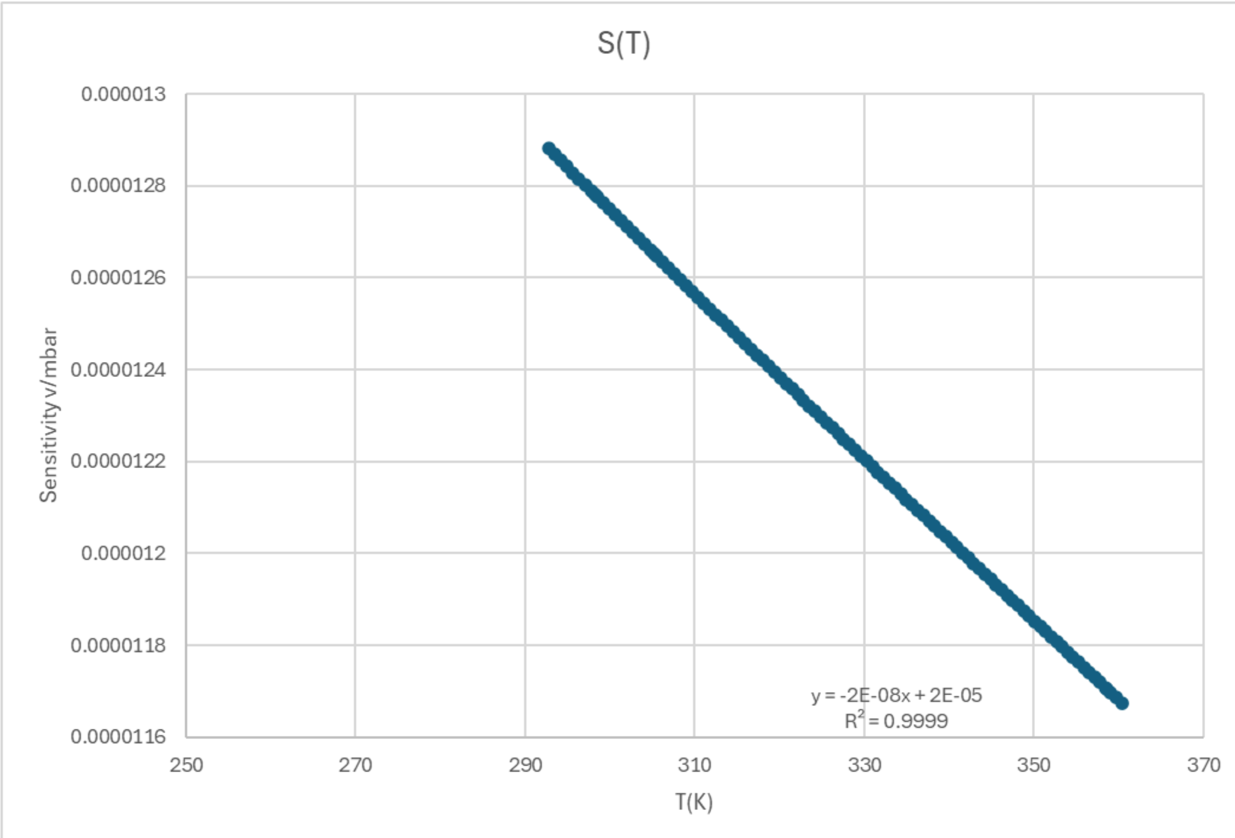

Figure 3.2 Sensitivity vs. Temperature

To address changes in sensitivity and offset as a result of temperature fluctuation, the method used employs two different resistor configurations. The first being resistors in series with the entire sensor, and a single resistor in parallel with a single branch of the sensor.

3.2.1. Offset Compensation

The movement of the offset voltage value is dampened by the placement of the parallel resistor. This damping effect can be customized for each sensor by placing the parallel resistor on either an arm that increases resistance with pressure, or one that decreases with pressure (Denoted as R17 and R18 in schematic respectively). When a parallel resistor is placed on the input side of the sensor, the equivalent resistance of the branch is reduced the larger the parallel resistance value. This causes an increase in offset voltage lowering the parallel resistance. The opposite effect happens when the resistor is placed on the lower end of the bridge, which creates a decrease in offset voltage. Using this tool offset can effectively be mitigated depending on the natural behavior of the sensor.

3.2.2. Sensitivity Compensation

The purpose of the series resistor is to reduce the input voltage coming into the sensor. Ultimately this reduces the increase in sensitivity with increased temperature, which will yield pressure/voltage trends that are parallel between different temperatures. The effect of this resistance is directly proportional with the resistance value. While there is no “limit” to how much series resistance one could add, there are certain set backs such as noise issues due to small input power magnitude.

3.2.3. Simulation and Design

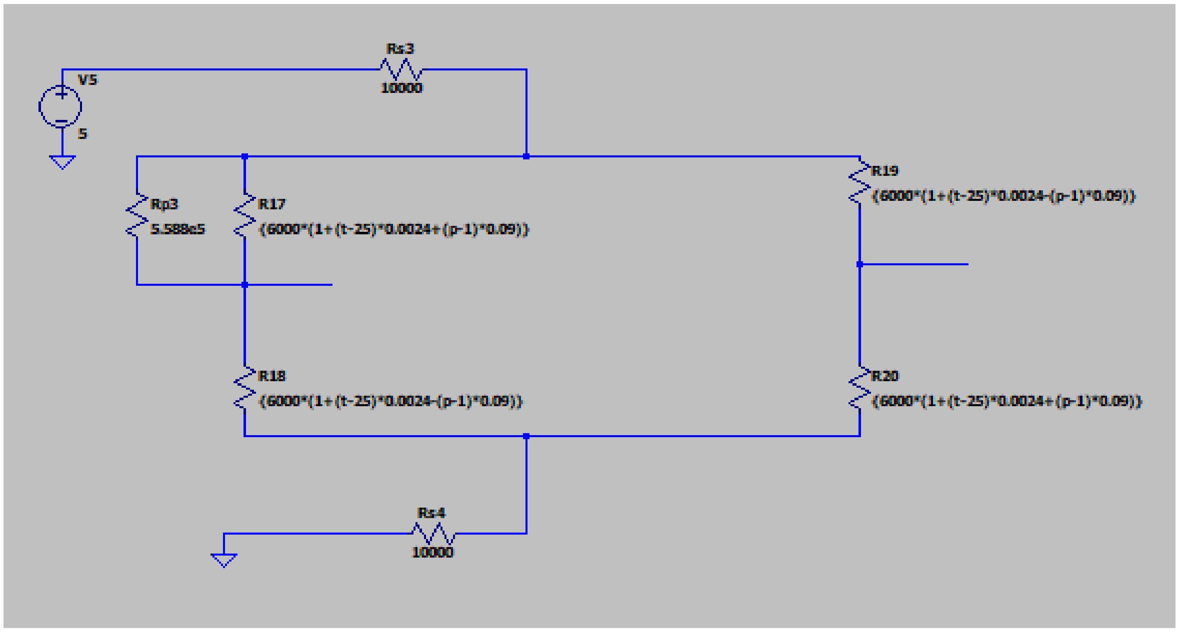

Figure 3.3 Final Design Schematic

Using calculated values of resistances and an equation modeling the full bridge sensor, I was able to simulate the behavior of the system under a range of temperatures. Under this model data found in simulations granted average error close to around 3%.

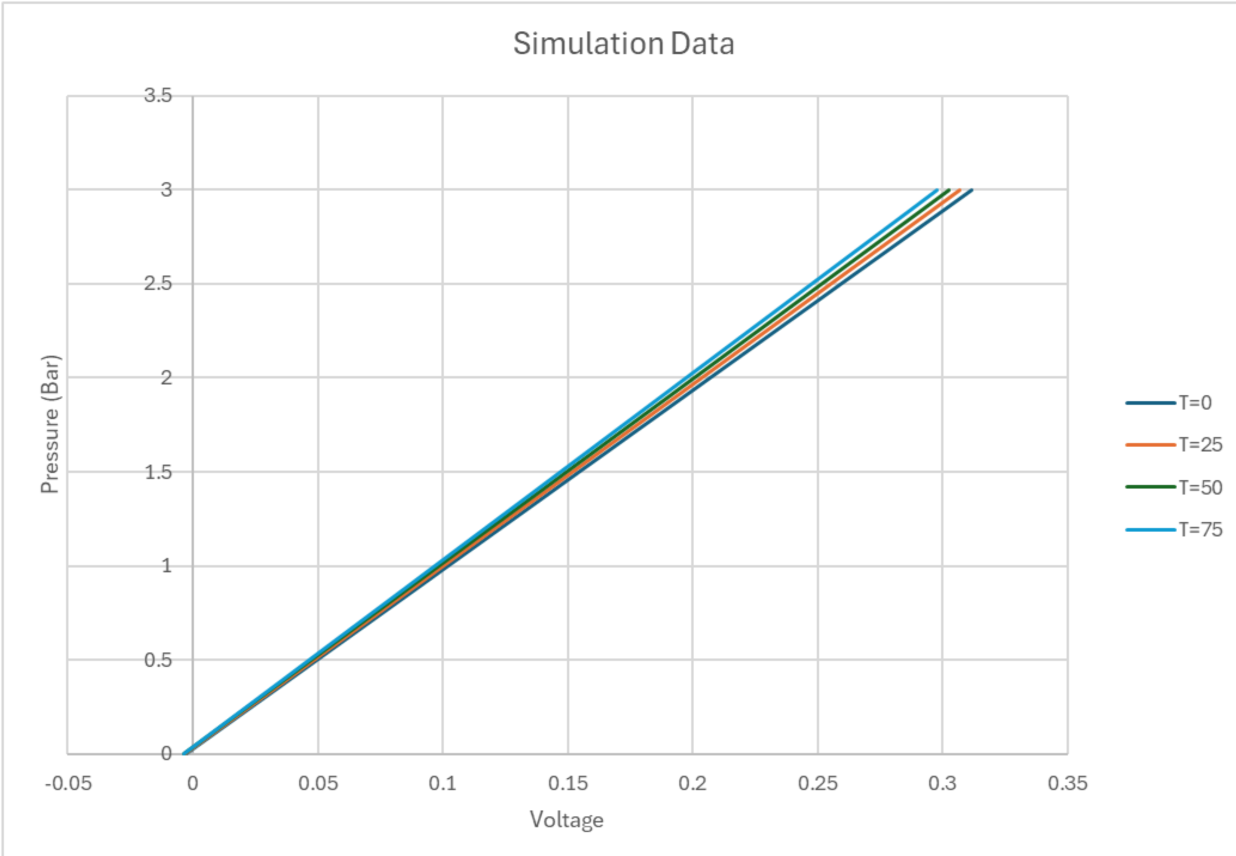

Figure 3.4 Simulation Curves

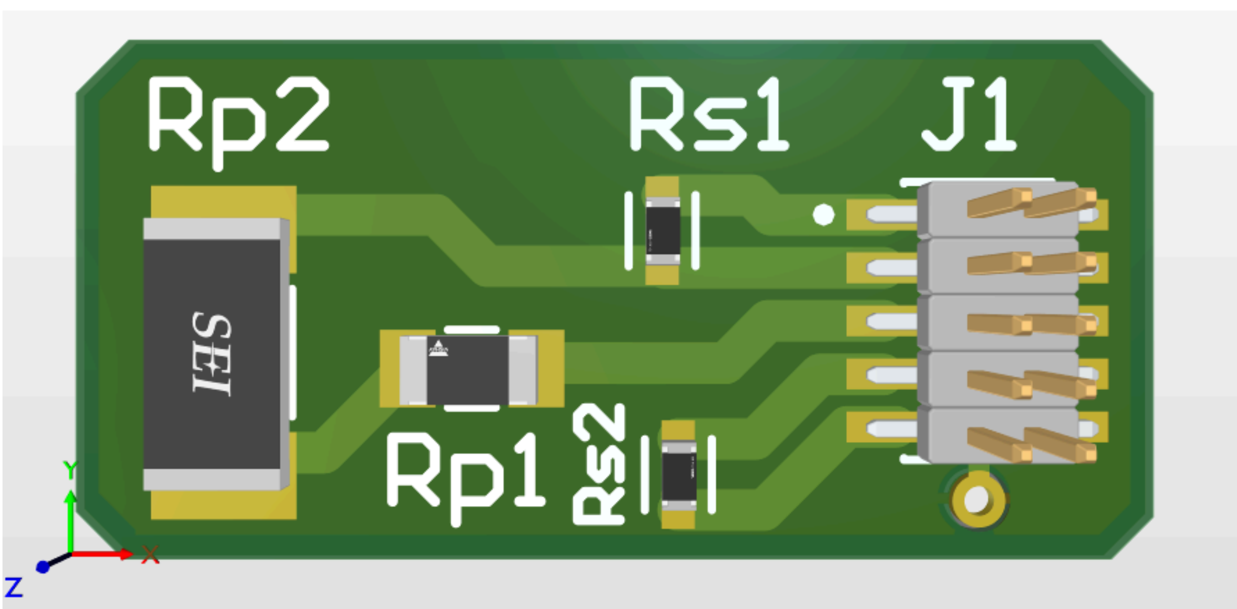

Figure 3.5 PCB Design

3.3. Validation and Results

To test the board design, a rudimentary sensor that simulates that of an actual piezoresistive sensor was developed using sets of resistors and potentiometers. To simulate different pressures and temperatures, resistances of each branch were calculated using our full bridge model and translated onto our sensor.

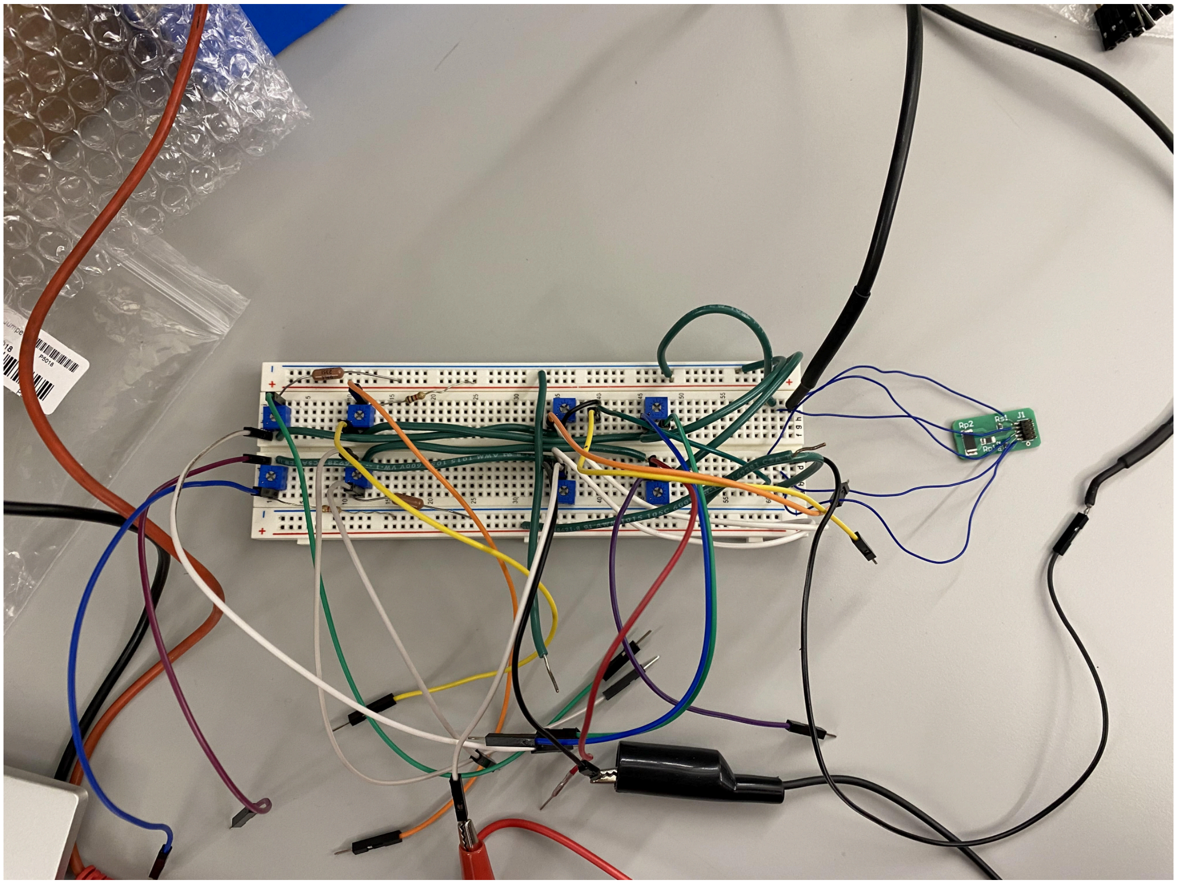

Figure 3.6 Sensor and Board Testing Setup

To validate the output voltage readings were taken from a range of 0 - 3 bars of pressure at temperatures of T0 = 0°C, T1 = 25°C, T2 = 40°C.

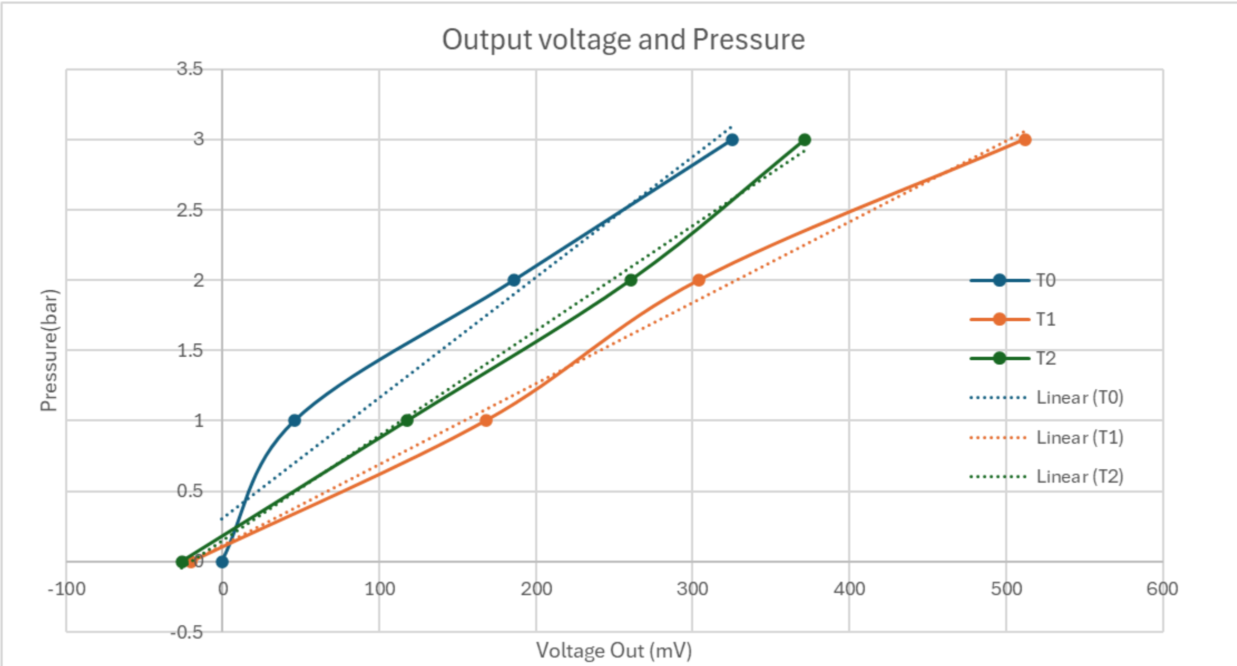

Figure 3.7 Testing Curves

In my findings, I noted a large swing in output values at magnitudes of 30mV at certain points. Output voltages past the reference temperature T0 also greatly surpassed the expected 0.3 V at 3 bar seen in simulation. The lines also did not follow the trend I expected. Notably T0, which had a smaller sensitivity compared to the other temperatures.

3.3.1. Offset Results

According to our results, the trend in offset followed similarly to how I would expect. Offsets for voltage readings decreased as temperature increased. However, the large negative values are undesired and vary much more than optimal. This implies a parallel resistance value that is high and is not properly compensating.

3.3.2. Sensitivity Results

In our data, the sensitivity behaved unexpectedly. While the sensitivity was greater than in the simulations in the higher temperatures, T0 displayed a sensitivity that was similar to that found in the simulation. This, however, compared to the other temperatures is much smaller. The trend was expected to be an increase of slope with increasing temperature.

Task	**Specification**	**Status**
Output Signal Limit	**0-150mV**	**Failed**
Maximum Area	**Area Shall not Exceed 6 in x 5 in**	**Passed**
Prediction Accuracy	**<3% error**	**Failed**

3.4. Conclusion and Failure Analysis

Overall, the board at its current state is not compensating as desired and does not fulfill some of the key validation required of our system. One issue that I have found is the testing procedure employed. Not only is manual manipulation of the sensor inaccurate, it is quite inefficient to change 8 potentiometers for a single reading. There is also the issue of having too few data points to see the proper behavior of the system. To address this, moving forward I plan on employing digital potentiometers to automate the process and record more accurate data. Our sponsor has also offered to allow us to test our systems on a true sensor using their materials. Noise was also a large issue in the system. The occurrence of fluctuations in the readings implies that the series resistances used were much too large, as well as the intense increase of sensitivity at the higher temperatures. Both resistances, in fact, need to be revisited as the offset compensation from the parallel resistor was not enough to unite the curves.