Course code and name:	B57GF - Engineering Praxis (GA) - 2022-2023
Type of assessment:	**Individual** (delete as appropriate)
Coursework Title:	Project Report
Student Name:	Imogen Heard
Student ID Number:	H00422897

Declaration of authorship. By signing this form:

- **I declare** that the work I have submitted for individual assessment OR the work I have contributed to a group assessment, is entirely my own. I have NOT taken the ideas, writings or inventions of another person and used these as if they were my own. My submission or my contribution to a group submission is expressed in my own words. Any uses made within this work of the ideas, writings or inventions of others, or of any existing sources of information (books, journals, websites, etc.) are properly acknowledged and listed in the references and/or acknowledgements section.

- I confirm that I have read, understood and followed the University's Regulations on plagiarism as published on the University's website, and that I am aware of the penalties that I will face should I not adhere to the University Regulations.

- I confirm that I have read, understood and avoided the different types of plagiarism explained in the University guidance on Academic Integrity and Plagiarism

Student Signature (type your name): Imogen Heard

Date: 23/06/2023

Copy this page and insert it into your coursework file in front of your title page.

For group assessment each group member must sign a separate form and all forms must be included with the group submission.

Your work will not be marked if a signed copy of this form is not included with your submission.

1. Table of Contents

1^{st} Year Project Report – Truss PCB

1 Summary/Abstract

This report focuses on a design project involving an embedded systems solution for analysing strain sensors applied to a truss structure in a teaching experiment.

The primary challenge addressed in this project was to optimise the manufacturing and assembly process, due to the large number of connections that need to be made between the truss structure and the control system. Additionally, the solution aimed to provide a reliable system, capable of constant operation over a 24/7 timeframe, as students are able to remotely access the experiment at any time between covering the materials in lectures and completing coursework, via a web interface. The experiment is designed to fulfil practical coursework requirements and achieve learning objectives within the mechanical engineering course.

To overcome these challenges, a custom-designed PCB was developed with a specific focus on economic data acquisition solutions, while maintaining ease of manufacturing, reliability and ease of maintenance.

The implemented solution successfully met expectations, aligning with the requirements of the teaching objectives and supporting the practical application of engineering theories through real-world experimentation.

2 Introduction

This design project is focused on producing a control and data acquisition system for the Remote Labs Truss Experiment. This is a structural mechanics teaching experiment in which a load is applied to a truss structure using an actuator, and the strain on each member is recorded with the use of strain sensors. As a previous report [1] dealt with the analysis of the truss structure, this design report will focus on the electronic design of the sensor and control system used to apply a load to the structure and collect the data from the strain sensors.

This project is relevant to engineering as applying structural mechanics theory to real world structures, measuring and analysing data and seeing how the real world deviates from theory is an important aspect of engineering education.

Although operating on a different scale, in large scale civil engineering projects, networks of strain sensors are often used to track loading on a structure, to account for wear over time, monitor health of structures and identify problems in a structure before they become dangerous. [2]

The objective of this activity is to produce a turnkey solution for measuring up to 6 strain gauges that are applied to the truss members of the truss experiment, as well as the data from the load cell which tracks the amount of force being applied to the structure. It should also be able to control the actuator which applies the load, and should include a safety limit switch to prevent the actuator from applying so much force that the experimental structure or actuator is damaged. The data will be gathered by a microcontroller, and this will be transferred via a serial data connection to a single-board computer that acts as a web server which the students can access in order to control the experiment.

3 Theory/Background

3.1 Strain

Strain is the change of the dimensions of a material in response to stress as a result of an applied load. Lateral Strain is relatively easy to measure directly, as the material under stress can be physically measured. It is defined as the ratio of an absolute change in length (ΔL) to the initial length, l_0, making it a dimensionless quantity. [3]

$$strain = \frac{\Delta L - l_0\ (m)}{l_0\ (m)}$$

Positive values of strain indicate that the material has increased in length due to applied tension, and negative values of strain indicate that the material has reduced in length due to compressive loading. It is also worth noting that for a material undergoing positive strain in one direction, it will experience negative strain along the perpendicular axis, and vice versa.

Strain can also be a result of shear stress, however this is beyond the scope of this design report, as the experiment deals with a loaded truss structure, in which it is assumed that all members undergo lateral stress only. Sheer stress should be negligible as all members are pin jointed, and therefore free to rotate around this axis, removing the possibility of them experiencing significant sheer stresses. [4]

Strain can occur within the elastic limit of materials, signifying that once the applied force is removed, the material will revert to its original shape. Beyond the limit of elasticity, the material experiences permanent deformation known as plastic deformation. In structural analysis, it is generally considered a failure of the structure if the material exceeds its limit of elasticity. Hence, all analysis presented in this report assumes that the materials remain within their elastic limit.

3.2 Inferring Stress from Strain measurements

When the strain of a material remains within its elastic limit, the stress is proportional to the strain. Therefore, by knowing the young's modulus, or modulus of elasticity of the material, strain measurements can be utilised to estimate the stress within the material.

The modulus of elasticity of a material quantifies the amount of strain a material undergoes given a specific applied stress. This information can be found in the materials datasheet for the acrylic sheet product that the truss is manufactured from. Consequently the stress in the structural member can be calculated using the formula: [5] [6]

$$stress\ (Nm^{-2}) = strain\ \times Elastic\ Modulus\ (Nm^{-2})$$

This also means that if the dimensions of the material are understood, the force being applied to the material can also be inferred. This makes strain sensors vital for understanding the otherwise unobservable forces acting on structures. [7]

$$force\ (N) = stress\ (Nm^{-2}) \times cross - sectional\ area\ (m^2)$$

These equations are not directly relevant to the design constraints of this data acquisition system, however, they will become important when the system is built in order to verify and validate the system by ensuring that the values the sensors are returning match the theoretical model of how the materials in the structure should deform under loading.

3.3 Strain sensor theory and operation

3.3.1 Strain Sensor Physical Construction

Strain sensors are physically simple devices. They consist of a substrate onto which a length of high resistance electrical wire is attached. The wire is run backwards and forwards over the area of the substrate, with the long edge in the direction of the strain to be measured, and the short edge perpendicular to the direction of the strain. This maximises the length of wire that is running parallel to the direction of strain.

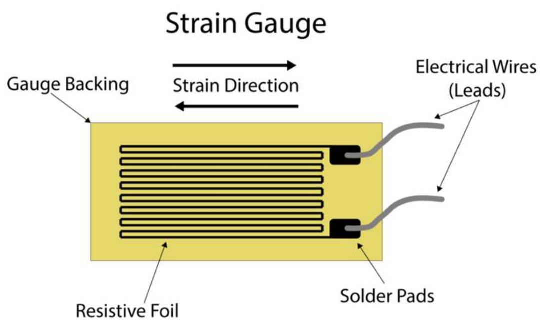


Figure 1 - Strain Gauge [8]

As the material the sensor is mounted to undergoes strain, the wires themselves are also subject to the same strain, and due to the electrical characteristics of the wire, the resistance changes. This is due to the same deformation that the structure is undergoing. If the strain gauge is undergoing positive strain, the wires are being stretched longer, thus slightly increasing resistance, and they are getting thinner due to the negative perpendicular strain, which also slightly increases the resistance. The change in electronic resistance of the wire can be quantified using the following equations. [9] [10] [11]

Where:

$R = Resistance\ (\Omega)$
$\rho = Resistivity\ of\ material\ (\Omega\mathrm{m})$
$l = Length\ of\ wire\ (m)$
$A = Cross - sectional\ Area\ (m^2)$

$$R_0 = \rho\frac{l}{A}$$

As volume is the cross sectional area multiplied by the length:

$$V = l \times A$$

Assume strain (ε) is applied to the wire, this will cause a change in the area

$$V = \Delta A \varepsilon l$$

As volume remains constant, equations for the original volume can be combined with the equation for the new volume:

$$\Delta A_0 \varepsilon l_0 = l_0 A_0$$

Rearrange to make the change in area the subject:

$$\Delta A_0 = \frac{l_0 A_0}{\varepsilon l_0}$$

Cancel like terms:

$$\Delta A_0 = \frac{A_0}{\varepsilon}$$

$$\Delta \mathrm{A}_0 = A_0\frac{1}{\varepsilon}$$

Therefore the change in area is equal to the old area divided by the strain, or multiplied by the inverse of strain.

Therefore given a strain of 1% or length = 101% of l_0, substituting in known values:

$$\Delta A = \frac{1}{1.01}A_0 = 0.99A$$

This can be substituted into the equation for the resistance:

$$R_{1\%} = \rho\frac{1.01l}{0.99A}$$

As all other values are constant, they can be omitted, this means that the change in resistance is:

$$\Delta R_{1\%} = \frac{1.01}{0.99}R_0$$

$$\Delta R_{1\%} = 1.02R_0$$

So for every 1% of change of length, the resistance of a single wire will change by 2%. This could also be shown as, doubling the length of the wire would make the resistance 4 times as large.

Therefore for the sensor in [Figure 1] the total change in resistance given a 1% strain would be:

$$\Delta R_{1\%} \approx R_0 + (2 \times 0.01)R_0 \approx 1.02R_0$$

And for the same sensor undergoing negative 1% strain:

$$\Delta R_{1\%} \approx R_0 + (2 \times -0.01)R_0 \approx 0.98R_0$$

Or for a more generalised formula:

$$R_\varepsilon \approx R_0 + 2\varepsilon R_0$$

Where ε is the value of strain.

This is only an approximate value as this does not account for the short connections between the parallel wires, which would be undergoing a change in resistance opposite to the wires running parallel.

This change in resistance, though significant, is not enough on its own to make reliable measurements, however the way the sensors are arranged in the circuit electrically is also designed to maximise the effect of this small change on the wider circuit.

3.3.2 Strain Sensor Electrical Construction – The Wheatstone Bridge

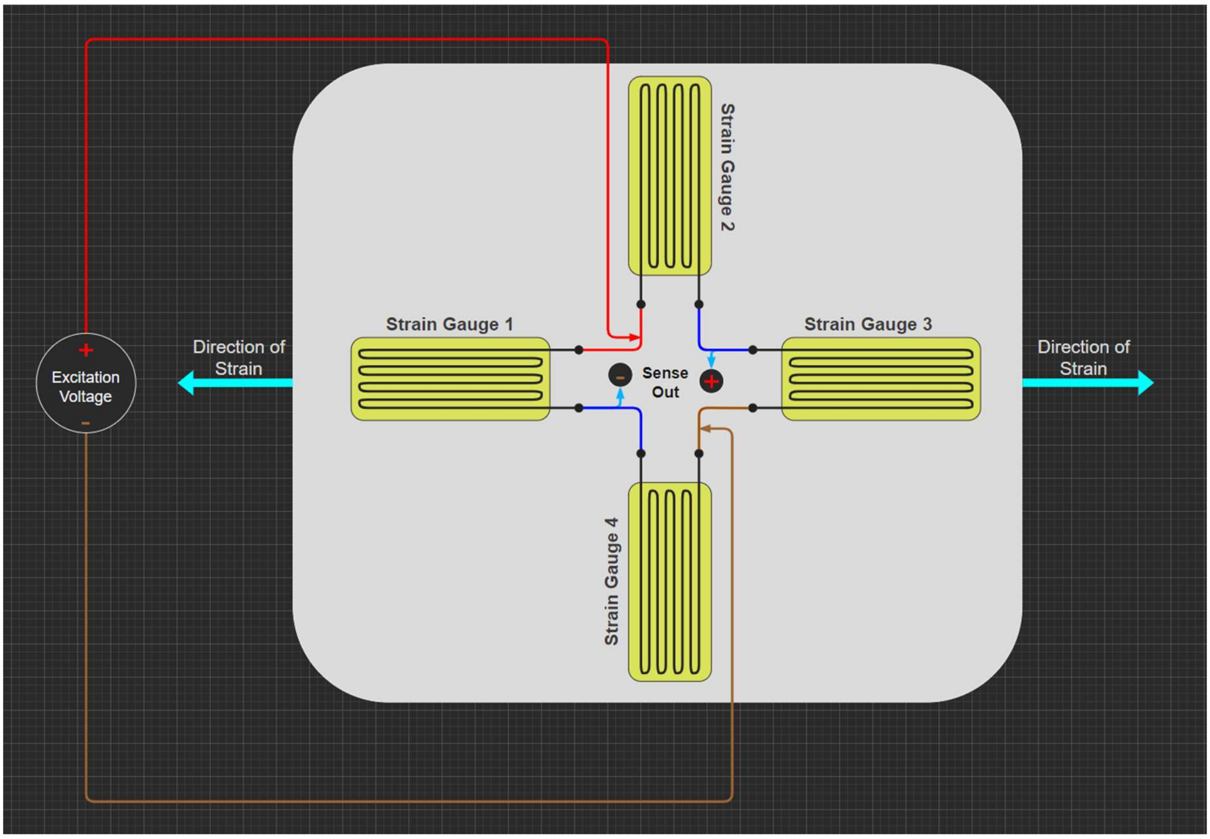


Figure 2 - Strain Sensor Wheatstone bridge Arrangement

Each individual strain gauge is wired into a Wheatstone bridge layout. This is a four node arrangement of variable resistors (Rheostats). An excitation voltage is applied to the node between two of the sensors, with the ground placed on the node opposite this one. This is in effect a pair of voltage dividers connected together, and the sensor signal is the differential voltage measured between the two other nodes in this 4 node arrangement. [8] For this specific sensor, each sensor has a nominal resistance of ≈100 ohms.

For measuring lateral strain, one pair of sensors is applied with the long wires pointing parallel to the lateral strain, and the other pair are applied with the long wires perpendicular to the applied strain. The sensors are paired with the sensor diagonally opposite, such that Sensor 1 and 3 will be parallel, and Sensors 2 and 4 would be parallel to each other (but perpendicular to 1 and 3).

The individual sensors in the diagram above are shown separately to make the schematic clear, but generally they are overlaid over each other in perpendicular pairs, with one pair placed on each side of the structural member.

In the circuit pictured above, The excitation voltage is at Node(1, 2), and ground for the excitation voltage is connected to Node(3, 4). The sensor output is from Node(2,3) and Node(1,4).

The following electrical schematic was generated in KiCAD to further explore the electrical characteristics of this circuit.

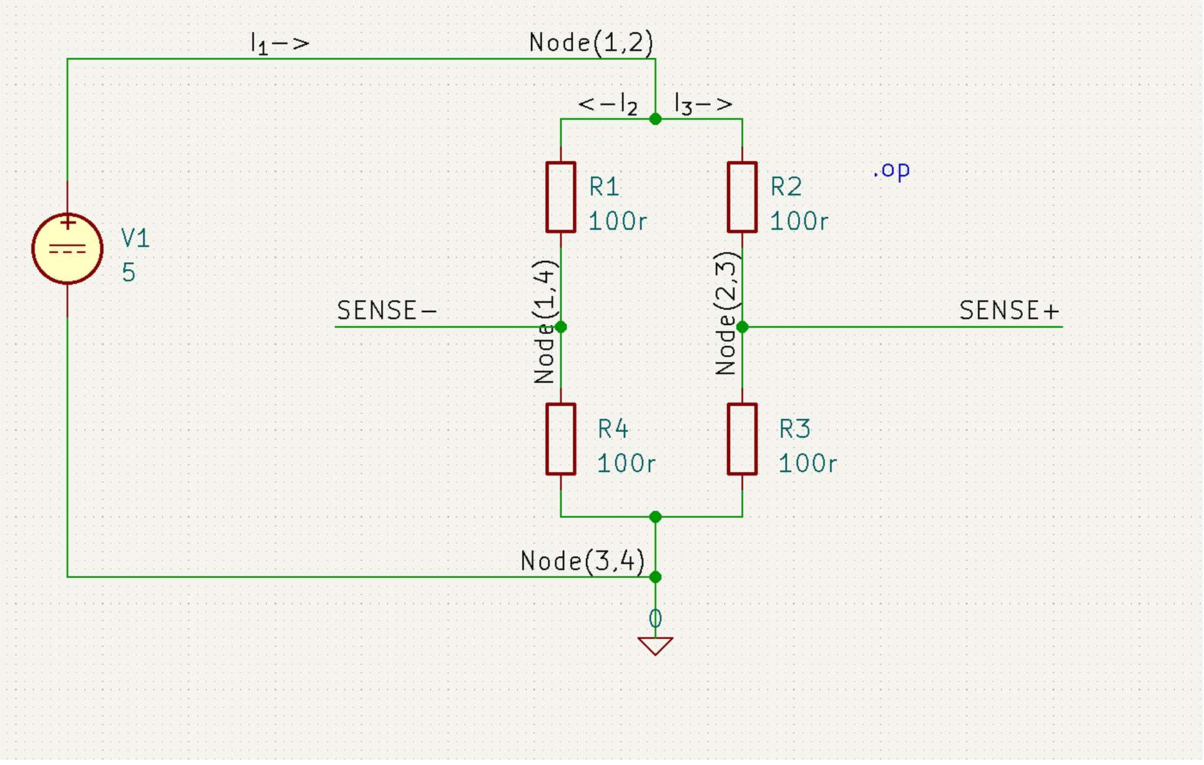


Figure 3 - Wheatstone Bridge Electrical Schematic

The following section undertakes some basic circuit analysis, although all variables are already known in this situation, it is important to document how these quantities relate to each other.

Sum of currents leaving node equal currents arriving at node. Kirchhoff's current law

$$I_1 = I_2 + I_3$$

Current I_1 is related to the nodal voltage V_1 and the total resistance of the circuit by ohms law.

$$I_1 = \frac{V}{R_{total}}$$

Calculating R_{total} for entire resistor network

$$\frac{1}{R_{total}} = \frac{1}{R_1 + R_4} + \frac{1}{R_2 + R_3}$$

$$R_{total} = \frac{1}{\left(\frac{1}{R_1 + R_4} + \frac{1}{R_2 + R_3}\right)}$$

Current I_2 is related to the nodal voltage V_1 by ohms law

$$I_2 = \frac{V_1}{R_1 + R_4}$$

Current I_3 is related to nodal voltage V_1 by ohms law

$$I_3 = \frac{V_1}{R_2 + R_3}$$

Substituting this into the equation for Kirchhoff's current law

$$\frac{V_1}{R_{total}} = \frac{V_1}{R_1 + R_4} + \frac{V_1}{R_2 + R_3}$$

However this circuit is best analysed as a pair of voltage dividers. The equation for the output of a voltage divider is as follows:

$$V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right)$$

Where R_2 is the resister over which the voltage is measured. In this case R_2 would refer to the resistors that are connected directly to ground.

As the SENSE+ and SENSE- nodes act as a voltage differential, the equation for the voltage between these two points is:

$$V_{diff} = V_{ex}\left(\frac{R_3}{R_2 + R_3}\right) - V_{ex}\left(\frac{R_4}{R_1 + R_4}\right)$$

This model was then simulated using Spice in KiCAD. Resistor R_5 was added to act as a stand in for the high impedance input to some kind of signal amplifier or microcontroller, and to force the Spice simulation to output the differential voltage, noted in the output as *"V(r5#branch)"*.

The voltage above ground of V_{sense+} and V_{sense-} are also shown in the output as *"V(/node_2_3)"* and *"V(/node_1_4)"*

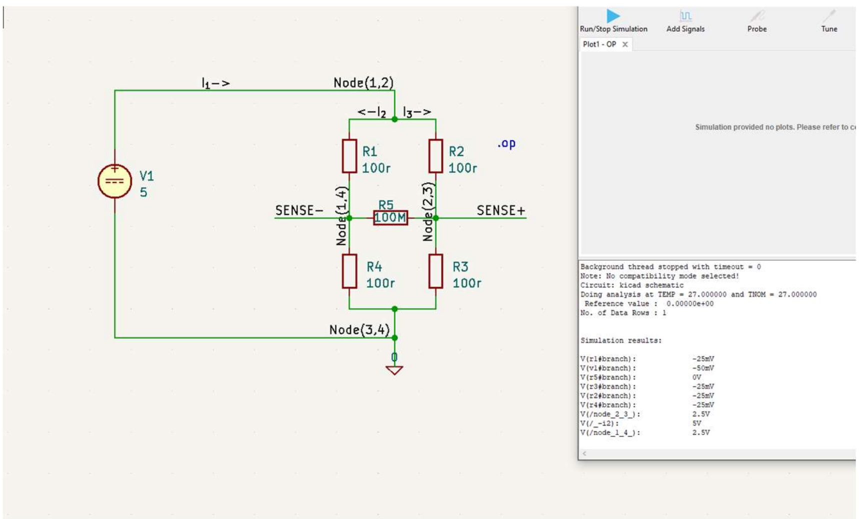


Figure 4 - Strain Sensor - Nominal State

This shows the expected result, that while the sensor is in its original state, Both $Vsense$ nodes are at 2.5v when referenced from ground, and the V_{diff} between them is 0.

In reality, it's highly improbable for this value to be exactly 0 due to manufacturing tolerances. As a result, there's usually a small voltage offset that needs to be considered when analysing the signals. This offset is accounted for by “Taring” the scale, or adding an offset variable to the result such that the output of the algorithm is zero when the sensor is unloaded. However, for rest of this analysis, it is assume that the tolerances are precise and the DC offset is zero.

Now the circuit can be simulated with a 1% strain.

Using the generalised formula for the specific strain sensors used, for the sensors undergoing positive strain:

$$R_{\varepsilon} \approx R_0 + 2\varepsilon R_0$$

Replacing known values

$$R_{0.1\%} \approx 100 + 2 \times 0.01 \times 100$$

$$R_{0.1\%} \approx 102\ ohm$$

And for the perpendicular sensors undergoing negative strain:

$$R_{0.1\%} \approx 100 + 2 \times -0.01 \times 100$$

$$R_{\Delta\varepsilon} \approx 98\ ohm$$

These values can now be placed into the equation developed for V_{diff} at 1% strain.

$$V_{diff} = V_{ex}\left(\frac{R_3}{R_2 + R_3}\right) - V_{ex}\left(\frac{R_4}{R_1 + R_4}\right)$$

$$V_{diff} = 5\left(\frac{102}{98 + 102}\right) - V_{ex}\left(\frac{98}{102 + 98}\right)$$

$$V_{diff} = 5\left(\frac{102}{200}\right) - 5\left(\frac{98}{200}\right)$$

$$V_{diff} = 5(0.51) - 5(0.49)$$

$$V_{diff} = 2.55 - 2.45$$

$$V_{diff} = 100\ mV$$

The circuit was also simulated in LTspice, and it shows a differential voltage of 100mV between sense+ and sense-

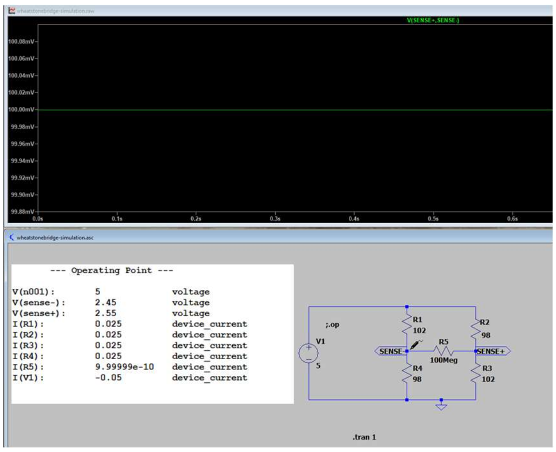


Figure 5 - LTspice Analysis of Strain Sensor under 1% Strain

Furthermore a model was built in Excel, which combined all the above mathematical models such that it is possible to input the excitation voltage, the strain gauge nominal resistance, and the percentage of strain, and gain an estimation for V_{diff} under these conditions, making a model that should work for any generic strain sensor.

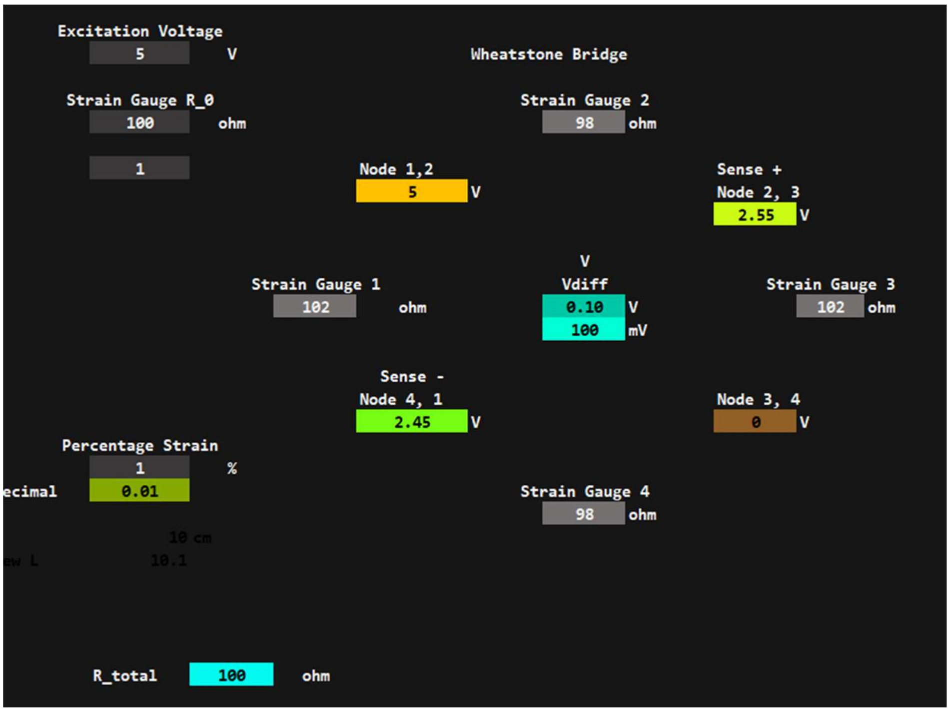


Figure 6 - Excel Model of Strain Sensor System

Using this model it was found that in order to achieve the maximum voltage swing of $V_{diff} = 5\ V$ the sensors would need to undergo a 50% strain. As the elongation at break of the acrylic material the truss is made from is between 3, and 6.5%, [12] and the elastic limit of the material will be far below this value, it shows that the full resolution of the Analog to Digital Converter (ADC) will never be achieved. A maximum voltage swing of much less than 300mV can be expected under normal test conditions with this apparatus. The equation to calculate the value returned by the ADC for a given voltage input is:

$$ADC_{value} = \frac{V_{in}}{\left(\frac{ADC_{V_{Max}}}{(2^{no.bits}) - 1}\right)}$$

Therefore for a 5 V microcontroller, with a 10 bit ADC:

$$ADC_{value} = \frac{0.3}{\left(\frac{5}{(2^{10}) - 1}\right)} = 61$$

As the variable returned by the ADC is an integer value it is truncated at the decimal point. Therefore the maximum resolution of the raw sensor, extending to the breaking point of the material would be approximately 61 individual steps. For this reason, amplifiers are used to condition the signal from the sensors and make it more suitable for use with higher voltage microcontroller ADCs.

4 Concepts & Concept Evaluation

4.1 Strain Sensor Amplifier

The first solution explored during development was a simple differential amplifier to amplify the maximum output of the sensor, 300mV to a 0 to 3.3 V or 0 to 5v signal. Depending on the microcontroller selected.

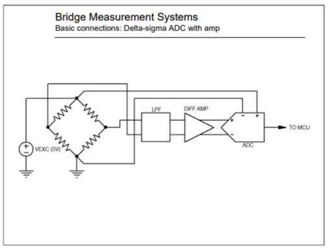


Figure 7 - Strain Sensor Amplifier - High Level Concept [13]

Some concepts for circuits were found in the TI application notes for Precision Analog Applications. One of the system diagrams suggested use of a differential amplifier, and a basic implementation of this topology was modelled in LTspice, using notes and schematic diagrams from electronics tutorials. [14]

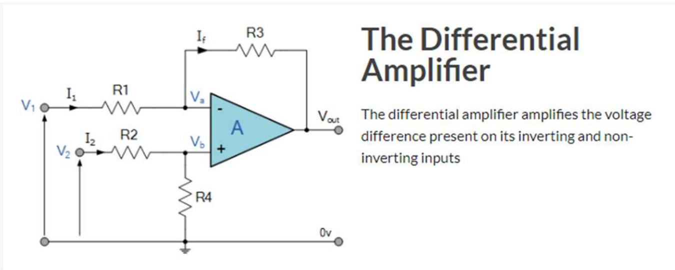


Figure 8 - Differential Amplifier [14]

Equation for a differential amplifier

$$V_{out} = \frac{R_3}{R_1}(V_2 - V_1)$$

Rearrange for R_3 given a low value, 100 Ω for R_1 as specified in the application notes from TI. V_{out} is specified to be 3.3 V as this will still be useable for a 5 V microcontroller, but resistor values can be recalculated later if additional resolution is required for a 5v microcontroller.

$$R_1 V_{out} = R_3(V_2 - V_1)$$

$$R_3 = \frac{R_1 V_{out}}{(V_2 - V_1)}$$

Substitute known values

$$R_3 = \frac{100 \times 3.3}{(0.3)}$$

$$R_3 = 1100\ \Omega$$

This is a resistor value that is available, or can be made with two easily available items. This circuit can now be modelled in LTspice.

4.1.1 Modelling a Differential Amplifier

In the first simulation, [Figure 9] 100r was selected for all of the resistors except the negative feedback resistor, which had been calculated as 1100 ohm. The model was programmed to sweep V_{sense} from 0 to 300mV to replicate the output of a strain sensor undergoing gradual loading to the elastic limit of the material.

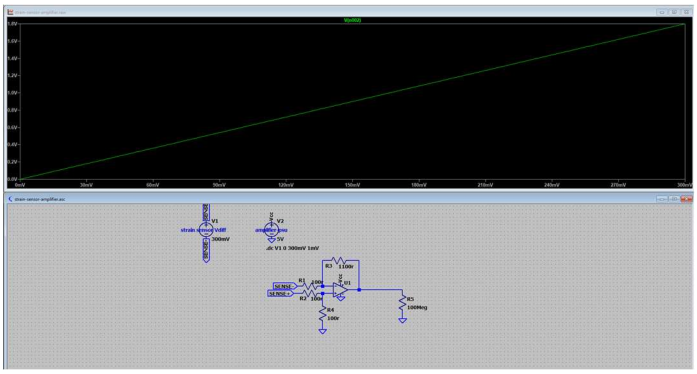


Figure 9 - Differential Amplifier - LTspice Analysis

However the voltage output did not achieve output voltage higher than 1.8v. It is believed to be because the resistor R4 is creating a voltage divider and cutting the voltage input to the non-inverting input in half. For this reason, a second simulation was run, this time replacing R_4 with a 10k resistor.

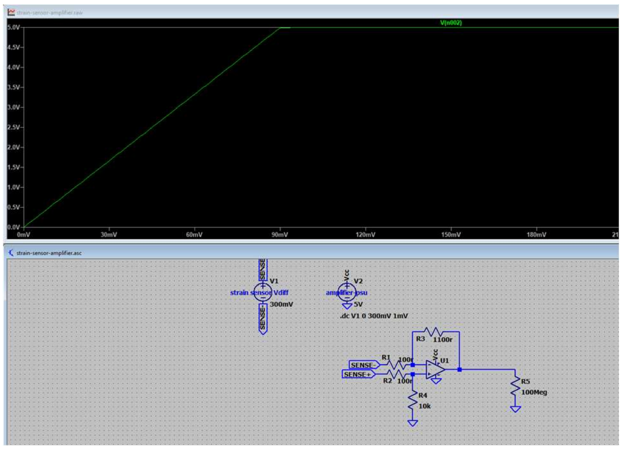


Figure 10 - Differential Amplifier - R4 = 10k

This plot showed non-linear behaviour past 90mV, the simulation was run a final time with $R_4 = 1\,k\Omega$

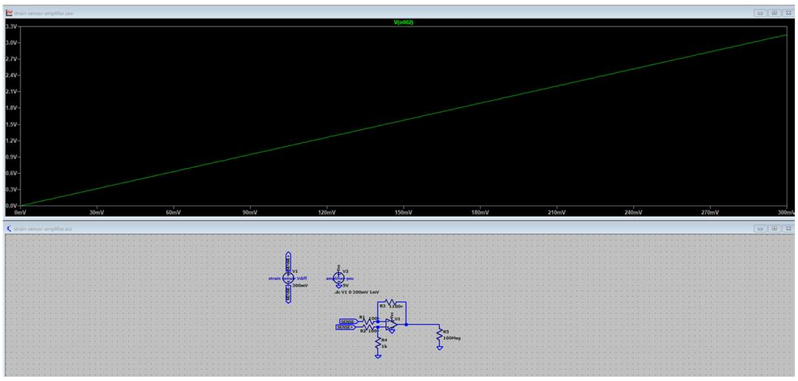


Figure 11 - Differential Amplifier - R4 = 1k

The plot is now linear until past the 3.0 V point, making this amplifier suitable for use with the specified Wheatstone bridge strain sensors.

4.2 COTS Option

In the process of examining alternative, Commercial Off-The-Shelf (COTS) options for sensor interfaces, Avia Semiconductor's HX711 IC was identified as a viable solution. [15] This integrated circuit offers the capability to provide the required excitation voltage, while also performing the analog-to-digital conversion process. Utilisation of this IC avoids the complexities associated with designing individual amplifiers for each sensor, and mitigate potential variations that might arise from the in circuit implementation.

This approach not only reduced the projects risk by minimising design time, but also removed unknown variables, like the operation of the amplifier circuit under real world conditions.

To assess the feasibility of this solution, samples of the HX711 IC development boards were procured and employed in an initial feasibility study on an early truss prototype. Although these tests were not quantified, the team found the results satisfactory, which consequently prompted the decision to adopt this solution for the production batch of PCBs.

5 Design Process

5.1 Electronic Schematic

5.1.1 High Level System Design

The initial high level system diagram was produced in KiCAD. This shows the direct exterior connections in and out of the PCB, as well as the hierarchical sheets for the various subsystems, including detailing all the inputs and outputs to each subsystem.

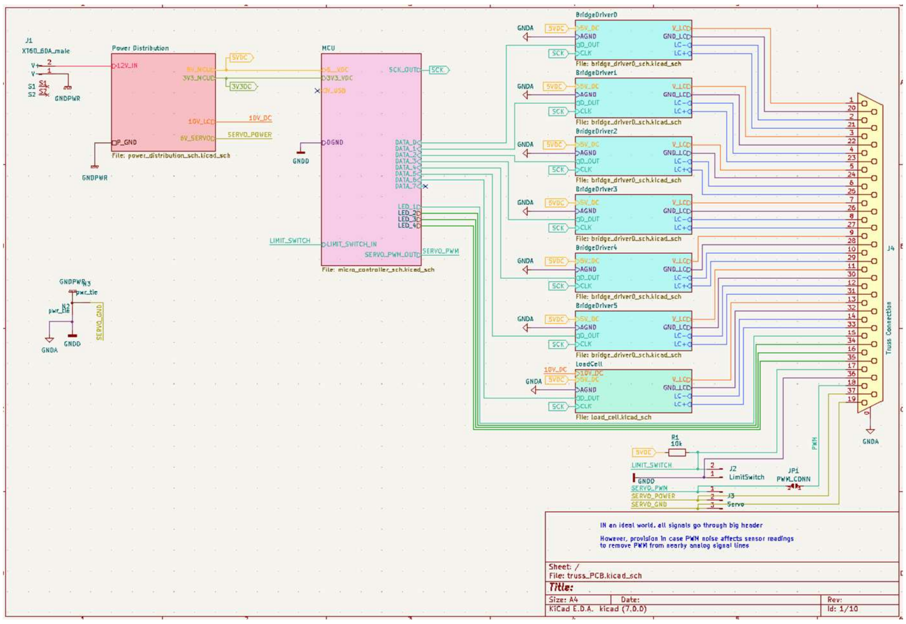


Figure 12 - High Level System Electronic Schematic

Different colours are used to identify net classes for each wire, which are assigned different rules depending on their function, for example power traces are carefully calculated for the expected current draw, using KiCAD's built in trace width calculator. Current draw estimations of the various sub systems and power bus were made where definitive information was not available in datasheets.

All sensor connections to the truss are routed through a 37 pin D-Sub connector. This is to enable quick connection to aid in quantity manufacturing, and to ensure that maintenance can be carried out quickly and effectively by unplugging a single connector to allow removal of the experimental hardware and gain access to the control system underneath. A separate connector was provided for the PPM signal used to drive a servo actuator, with a breakable trace leading to the D-Sub connector. This was to enable users to route potentially noisy PWM signals away from the analog signals carried by a ribbon cable connecting the truss experiment apparatus to the control PCB, though during testing it was found that noise was not an issue.

5.1.2 Power Supply Subsystem

The power supply to the control PCB was specified to be 12 VDC, as this is what the remote labs infrastructure provides. This was regulated through a series of low dropout linear regulators to 10 VDC for the load cell excitation voltage, 5 VDC for the HX711 ICs and 3.3V for the microcontroller. Additionally a higher current buck converter was placed in order to provide 6v to the servo. All of these implementations have been previously deployed and tested in various projects, both within and outside of the Remote Labs ecosystem, to ensure their effectiveness and reliability through extensive hours of usage. This sub system includes reverse voltage protection using an IRF3505 MOSFET, which had been proven effective in an earlier Remote Labs project.

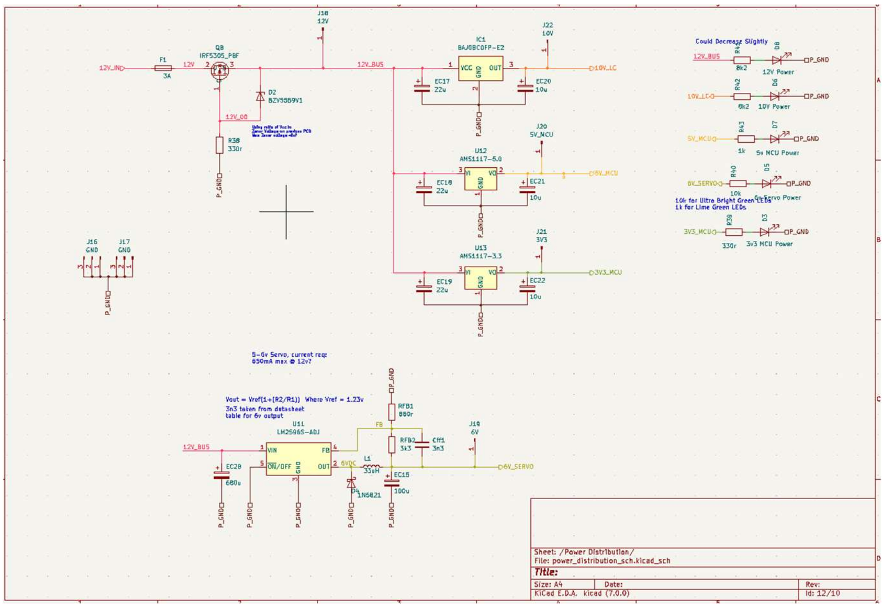


Figure 13 - Power Subsystem

5.1.3 Microcontroller Subsystem

The microcontroller was specified as an Arduino Nano IoT 33, as this is a platform RemoteLabs was already using, and the use of open source and accessible hardware is central to the Remote Labs projects core values. Using a COTS microcontroller development board also lowered the design time and risk in producing a PCB layout for a microcontroller that includes all the required peripherals like clock circuitry and USB communications. As the microcontroller selected uses 3.3v logic, and HX711 IC uses 5v logic, logic level conversion ICs were utilised to bridge these two subsystems. Solder jumpers were provided to bypass these ICs and ensure that the PCB could still be utilised if later changes were made to a 5v microcontroller. This is one of the many design choices made to standardise and futureproof electronics systems inside the Remote Labs environment.

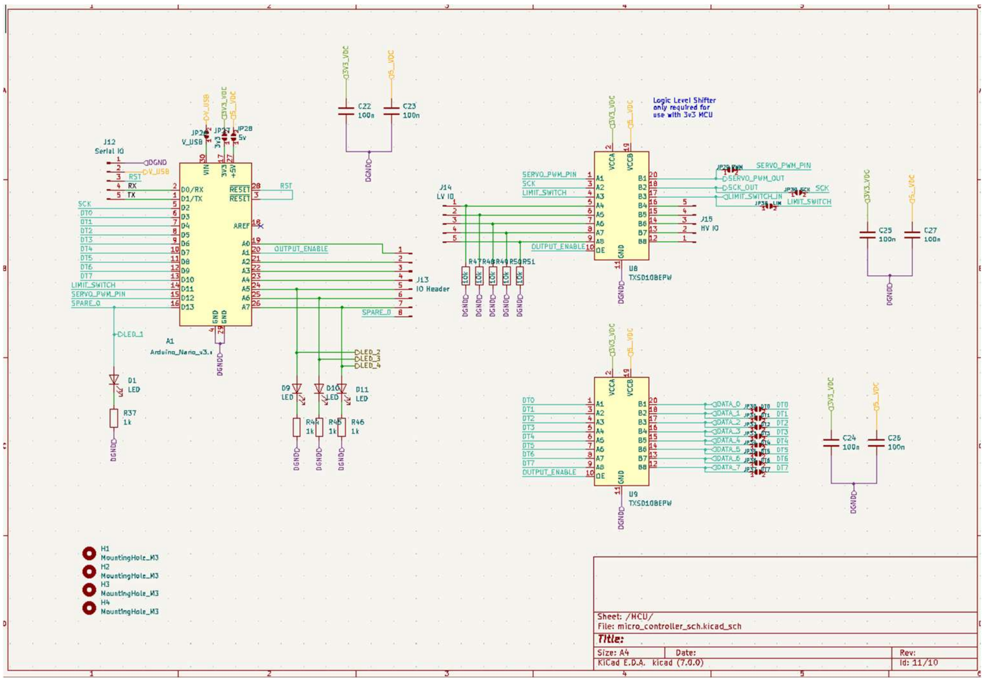


Figure 14 - Microcontroller and Digital Subsystem

5.1.4 Bridge Driver Subsystem

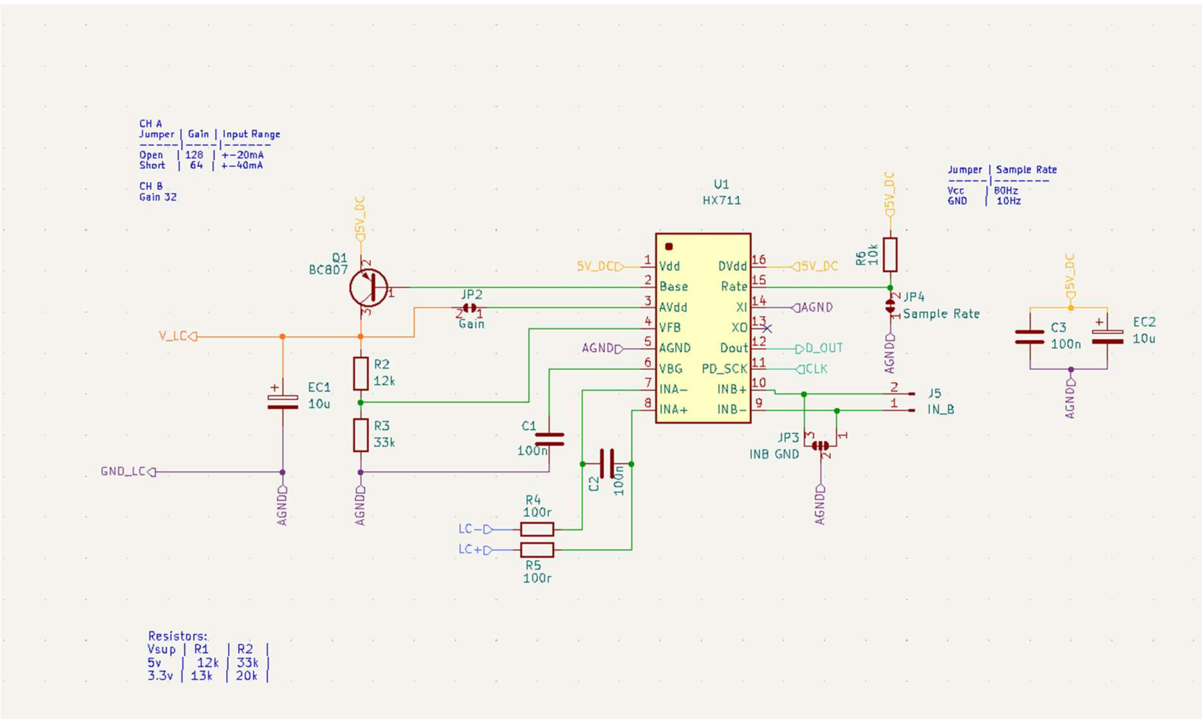


Figure 15 - HX711 Bridge Driver Subsystem

The HX711 implementation was taken from both the development boards utilised for an early prototype, and the HC711 datasheet application notes. [15] Jumpers were provided to ensure that the PCB could be easily adapted for different use cases, or fixed without major modifications where the correct implementation of the circuit was not clear from the application notes. This is a design choice made to lower project risk.

Using hierarchical sheets for the bridge driver implementation ensured that this subsystem could be copied into the schematic for each strain sensor channel required for the project, avoiding duplication of work and keeping the top level schematic looking clean and easy to work with.

5.2 PCB Layout

The layout was finalised using EEE CAD software package, KiCAD.

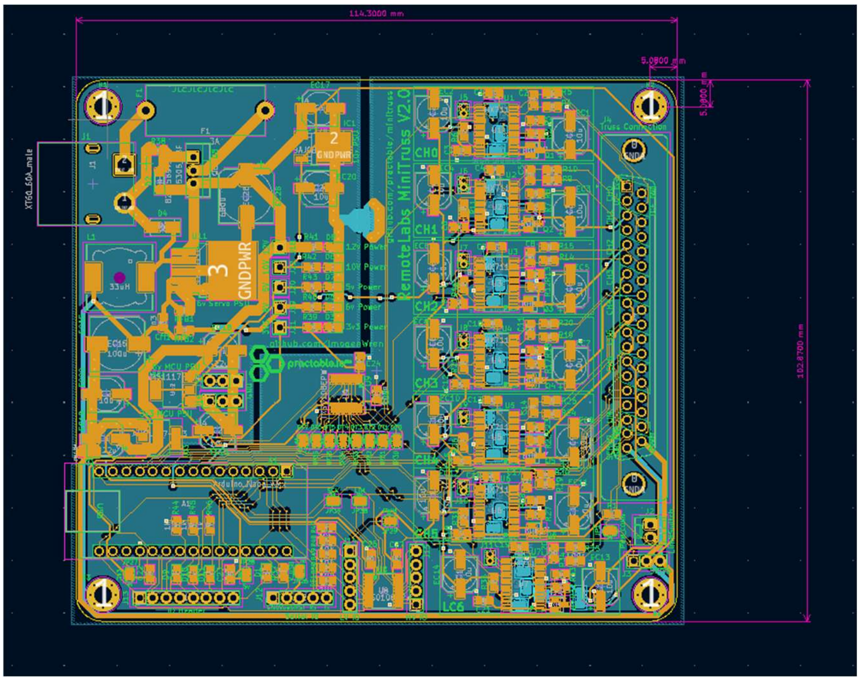


Figure 16 - PCB Layout

Notable design choices was the decision to separate power ground and signal grounds into two distinct areas, and joined only at a single point. The intent was to lower the noise floor in the analog pathways, and avoid clock noise from the buck converter affecting the data acquisition. The microcontroller and digital systems was also placed as far away as possible from the analog subsystems.

A 2nd, daughterboard PCB was also designed alongside the item pictured in order to provide screw terminal connections for each of the strain gauges. This would sit on the frame of the truss experiment and connect to the control PCB via a ribbon cable. This cut the time required to assemble a complete experiment in half, and allowed easy disconnection for maintenance.

5.3 Rendering

KiCAD was used to produce a 3D rendering of the final PCB design. This was exported as a STEP file and used in the CAD design for the enclosure and mounting for both the PCB and the experimental hardware.

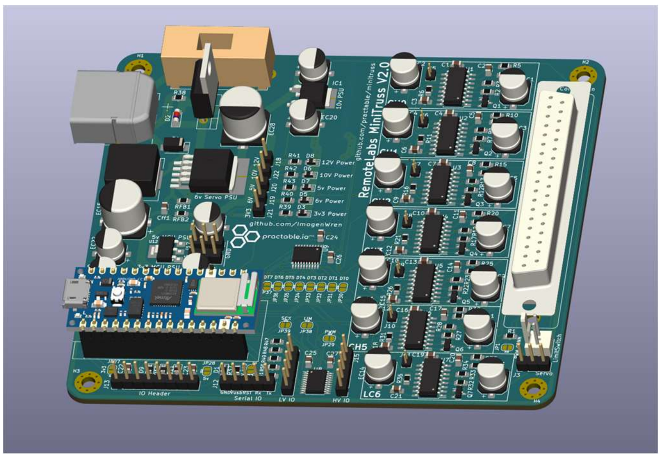


Figure 17 - CAD Rendering of completed Control PCB

5.4 Finished Product Photos

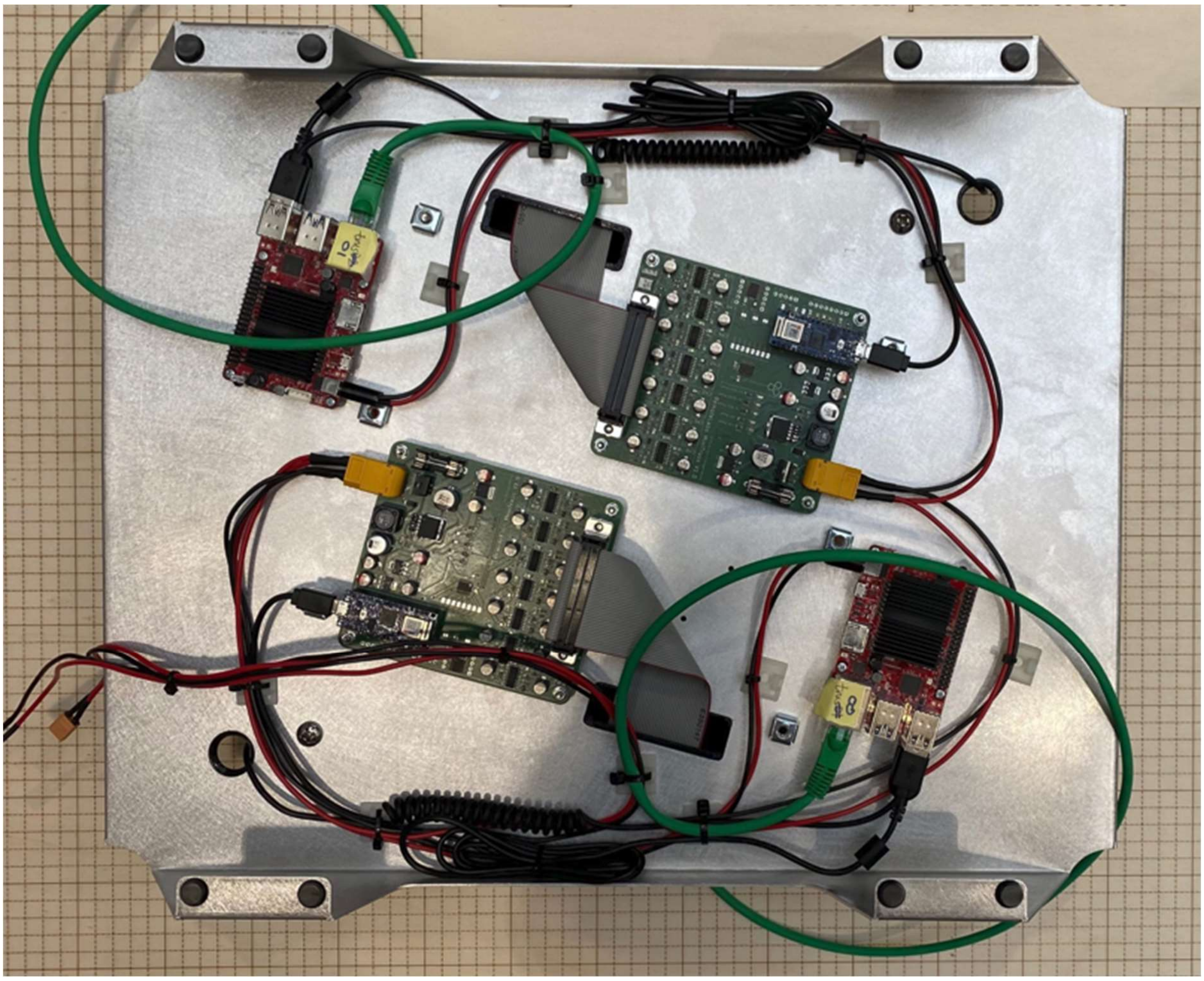


Figure 18 - Truss Experiment tray showing control hardware for two truss experiments.

Figure 19 - Finished Truss Experiment Container with 4x Truss Experiments.

6 System Validation

6.1 Test Rig

The test rig was made by suspending a single truss member with strain gauges, vertically such that it was able to be loaded with a pre-defined weight of 10 N. The strain sensor was attached to channel 0, and a program was compiled in order to read the strain values using an Arduino Nano IoT, using a library for the HX711 IC.

Figure 21 - Truss System - Test Rig

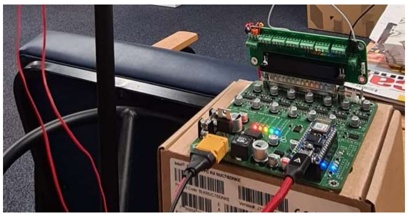


Figure 20 - Test Setup showing Adaptor Daughterboard

6.2 System Calibration

In order to use this system to measure strain in the truss experiment, the scale must be calibrated in software. The usual way to do this using a library provided for use with the HX711 IC, is to test the scale without a load, then apply a known force to the strain sensor, and use the value reported to generate a scale variable. This scale is then used for any further readings conducted by the microcontroller.

The initial calibration test was performed with a 10N weight. The table below displays the C++ Arduino code used directly for calibrating and outputting the data from the strain gauges, along with a description of the action of the program and user to calibrate the scale.

Table 1- Code & Action – System Calibration

Arduino C++ Code	System Action
`sensorArray[channel].set_scale(); // Step 1`	Step 1: Scale is set to null (no value) before performing calibration
`tareScale(channel); // Step 2`	Step 2: Scale is tared to ensure offset is nullified.

`Serial.println("Now Calibrating Scale");`
`Serial.println("Place a known weight on the scale..."); // Known weight in this case is 1 N, however the strain value this should result in ~373n strain or 0.373u strain.`
`countdown(5);`
`Serial.println("Taking Test Measurements");`
`countdown(5);`
	Countdown function used to give user time to change system configuration, apply weight and allow system to settle before readings are taken

`long reading = sensorArray[channel].get_units(10); // Step 3`
`Serial.print("Test Reading: ");`
`Serial.println(reading);`
`delay(500);`
	Step 3:
	Known weight is added to test rig.
	ADC is sampled 10 times and results are averaged.

`// Step 4: Divide the result in step 3 to known weight. You should get about the parameter you need to pass to set_scale().`
`// Calculation is reading/scale = known_weight or reading/known_weight = scale`
`scale_val = float(reading) / known_weight;`
	Step 4:
	Scale value is calculated using the reading from step 3, and the known weight value.

`Serial.print("scale_val: ");`
`Serial.println(scale_val);`
`sensorArray[channel].set_scale(scale_val); // Step 5`
	Step 5:
	Scale value is saved into the library to use on further readings.

Once the scale value is saved, the weight is removed from the test rig, and the scale is tared once again. The system is now ready for validation testing.

6.3 Validation Testing

In order to validate the system, the same weight used during calibration was used to compare the unloaded truss member, to the loaded truss member. The following table shows the reported values taken by the HX711 ADC after the calibration had been performed, both with and without the test weight applied.

6.4 Results

In each case the system was allowed to settle before 10 samples were taken. Results shown below

Table 2 - Validation Test Results

Sample	Actual Force (N)	Reported Force (N)	Deviation from True Value
1	0	0.3347	0.3347
2	0	1.1768	1.1768
3	0	1.3023	1.3023
4	0	1.6841	1.6841
5	0	1.4226	1.4226
6	0	1.3075	1.3075
7	0	0.7374	0.7374
8	0	1.0251	1.0251
9	0	1.318	1.318
10	0	0.7427	0.7427
1	10	9.1527	-0.8473
2	10	9.1789	-0.8211
3	10	9.1318	-0.8682
4	10	8.8389	-1.1611
5	10	9.1056	-0.8944
6	10	9.0638	-0.9362
7	10	8.2008	-1.7992
8	10	9.1109	-0.8891
9	10	8.3525	-1.6475
10	10	8.8703	-1.1297

7 Results/Validation & Discussion

7.1 Analysis

Analysis of this data was a little difficult, given the wide range of data for a given system configuration. The decision was made to plot each range of data separately in order to calculate the standard deviation of the results for each configuration.

First, the results from the unloaded truss member, or 0 N loading:

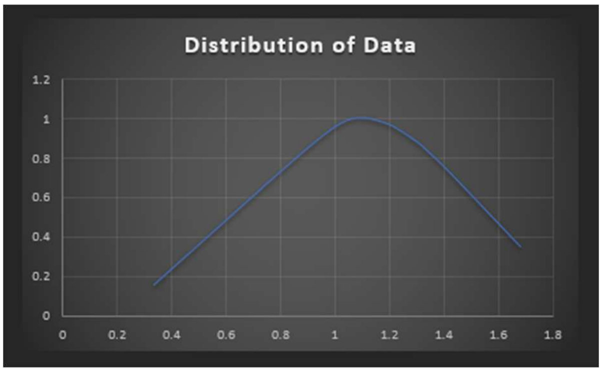


Figure 22 - Distribution of Data: 0 N Loading

The mean value for this set of data is 1.10512. With a standard deviation of 0.339.

Then the results from the loaded truss member, or 10 N loading.

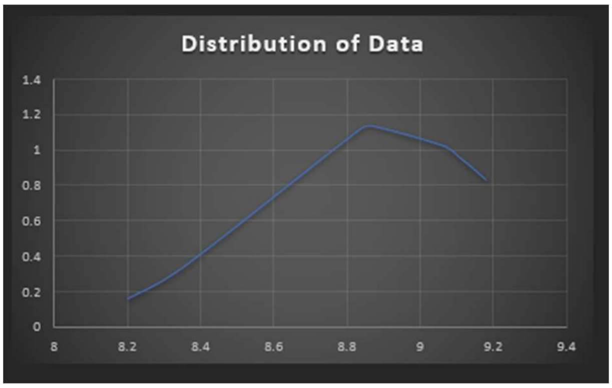


Figure 23 - Distribution of Data: 10 N Loading

The mean value of this set of data is 8.90062, with a standard deviation of 0.34995

Although these values are not exactly the values expected, these results show that some useful data is being generated, and that the load cells themselves are functioning as expected, though not with the level of repeatability that was initially envisioned.

After discussion with the academic who initially developed the truss system, it was made clear that a result within 10% of the correct value was nominal for the strain sensors used in the experiment.

7.2 User Experiences

As this system has now been in use for an entire teaching semester, user feedback from both academics teaching the courses and students who interact with the experiment are able to be gathered.

One notable experience comes from an Academic teaching mechanical engineering, and they raised points about the value of the remote labs environment and the Truss experiment in making students think about the process of data acquisition, inherent noise and consistent bias or drift that means experimental data needs to be processed in order to clean data to a useable standard.

"When students see the strain value changing from one reading to the next, they're often not sure what to do about that, and they get particularly concerned when they set all the strains to zero at zero load, using the "tare" button, and then they go through the next update and they're not zero any more.

We get them to think about what noise does to a measurement like this, and what the source of the noise might be." [16]

This testimony from the Academic staff was backed up by several students who affirmed that the learning experience undertaking the truss experiment was valuable, as it both allowed them to see the transmission of forces through a structure for themselves, and also taught them the value of data processing, and allowed them an opportunity to apply statistical analysis to the data they are collecting.

7.3 Validation Discussion

As this experiment is designed as a learning tool, rather than a research tool, or a method of accurately monitoring a live structure with real-world consequences was it to fail, the precision of this system is not the biggest factor in its viability. As long as it has sufficient precision to enable students to gather data needed to complete their coursework, and see the action of engineering mechanics in some kind of real world system, then the experimental setup is viable as a teaching experience.

The PCBs manufactured for this experiment had an end user price of approximately £35 each. An alternative system for data acquisition equipment, like cDAQ from National Instruments could run into thousands of pounds, which would make giving large classes of students' direct access expensive. The remote labs infrastructure allowed every student enrolled on the course 24 hour access to this experiment, using a total of just 8 individual truss experiments, split across 2 remote labs containers.

If this system was being used in an industrial application, the software would likely need to take many samples and average them before reporting the average value to the user. It may even be necessary to use multiple sensors for the same structural member so results can be compared and averaged to make up for discrepancies between individual sensors.

7.4 Improvements

There are three main issues that still remain with the assembly and use of this system.

The first is the application of the strain gauges to the individual truss members. This is still a very labour intensive process and requires fine motor control from trained individuals. The system as developed does not address this issue, however this problem has been discussed and no solution has been found. The use of pre-assembled load cells is not suitable for this experiment as it would require different materials to form each truss member, which would increase the complexity of the theoretical model, and make it harder for students to follow trends in the data that allow them to link the physical experiment and the data it produces, to the engineering theory they are learning.

The 2nd issue is identifying the wires which are directly soldered to the strain gauges. During manufacture care was taken to ensure that each gauge was applied in the same orientation, ensuring that visual inspection and comparison to a prototype would be sufficient to ensure each wire was labelled correctly. Once the labels were applied to each wire, the labels on the daughterboard PCB silkscreen provided a simple reference to ensure the correct wires were plugged into the correct channel. However this system relied on the first step being undertaken correctly, so a better system could be envisioned.

Lastly the data was exceptionally noisy. This may be due to a combination of material creep during loading and unloading, inaccuracy of the sensors, misapplication of the sensors to the truss members and difficulty calibrating the system. For future iterations it would be worth exploring different materials, such as metals that may not experience creep, different models of strain sensor that may improve accuracy and better methods for applying the strain sensors, for example use of a jig may assist in production line assembly.

8 Conclusions

The objective of this project was to build a system that would allow students to conduct experiments regarding the mechanical function and load transmission of truss structures. This equipment has now been in use for one academic year and forms part of the marked coursework for students undertaking mechanical engineering courses. Given the positive feedback from both Academics involved in teaching this material, and the students who used the equipment as part of their marked coursework, the project is deemed a success. The addition of a daughterboard PCB with screw terminals ensured that the wiring could be completed by mechanical technicians as part of a solderless production line, which sped up the assembly process and reduced the level of skill required during the final assembly.

- Gather Data and report strain values for up to 6 truss members and load cell [√]
- Control actuator to apply load to the structure, including limit switch [√]
- Provide an affordable solution for controlling this experiment in a way that allows easy access for students undertaking study in this area [√]
- Improve manufacturing and assembly times, decrease the level of skills required for assembly, and improve uniformity of the final product. [√]
- Maintain Commitment to Open Source and low cost hardware. [√]

9 Reflections

Through the process of writing this report, I came to a much greater understanding of the system that I helped design and commission the year before. Although much of the electronic design was undertaken without a complete understanding of the mechanical aspects, or the function of the load cells, this analysis gave me a deeper understanding of each of the elements of the system, from the force being applied to a structural element, to the data being presented to the student. Due to the discussions with Academic staff about the system and the behaviour of students while interacting with the experiment, a greater understanding of the value of these kinds of experiments as a learning tool, as well as an understanding of how students learn to deal with messy data from real world systems.

10 References

[1] I, Heard (2023, April 21st) *Strength of Materials Report* [Unpublished] Heriot-Watt University, Edinburgh.

[2] A. Alonso-Ramos, et al., (2022, 20th March) "*Concise Historic Overview of Strain Sensors Used in the Monitoring of Civil Structures: The First One Hundred Years*" Sensors, vol. 22, no. 6, article no. 2397, accessed June 15, 2023. [Online]. Available: https://www.mdpi.com/1424-8220/22/6/2397.

[3] *"Stress & Strain: Introduction,"* B57GM - S - Unit 2.0, Heriot-Watt University, Edinburgh accessed June 15, 2023. [Online] Available: https://canvas.hw.ac.uk/courses/19326/pages/unit-s2-stress-and-strain?module_item_id=1447265.

[4] *"Trusses: Introduction," B57GM – S – Unit 1.0,* Heriot-Watt University, Edinburgh accessed June 15, 2023. [Online] Available: https://canvas.hw.ac.uk/courses/19326/files/2002229.

[5] The Editors of Encyclopædia Britannica, (2023, 12th May,) *"Young's modulus,"* Encyclopædia Britannica, accessed June 15, 2023. [Online]. Available: https://www.britannica.com/science/Youngs-modulus.

[6] A. S. Kalu, *"Modulus of Elasticity,"* Florida A&M University, accessed June 15, 2023. [Online]. Available: https://web1.eng.famu.fsu.edu/~kalu/ema5226/02/topics/chap1/Kalu-g.pdf.

[7] Baumer Group, (2023) *"Function of Strain Sensors,"* accessed June 15, 2023. [Online]. Available: https://www.baumer.com/ch/en/service-support/function-principle/function-of-strain-sensors/a/function-strain-sensors.

[8] T. Nachazel, (2020, 13th August) "*What is a Strain Gauge and How Does it Work?,*" Michigan Scientific Corporation, accessed June 15, 2023. [Online]. Available: https://www.michsci.com/what-is-a-strain-gauge/.

[9] Vedantu, (2023, 10th June) *"If a Wire of Resistance R is Stretched to Double Its Length, Then Its Resistance Will Be:"* accessed June 15, 2023. [Online]. Available: https://www.vedantu.com/question-answer/if-a-wire-of-resistance-r-is-stretched-to-double-class-12-physics-jee-main-5f6d339fe3ff7e1c8025552b.

[10] U.S. Environmental Protection Agency, (2023, 21st March) *"Electrical Conductivity and Resistivity*," accessed June 15, 2023. [Online]. Available: https://www.epa.gov/environmental-geophysics/electrical-conductivity-and-resistivity#:~:text=Resistivity%20(%CF%81)%20is%20the%20inverse,are%20Ohm%20meters%20(%CE%A9m).

[11] The Editors of Encyclopædia Britannica, (2023, 24th May,) *"Resistivity,"* Encyclopedia Britannica, accessed June 15, 2023. [Online]. Available: https://www.britannica.com/science/resistivity.

[12] "*MATDATA - Online Materials Database*," accessed June 15, 2023. [Online]. Available: https://www.matweb.com/search/DataSheet.aspx?MatGUID=3cb08da2a0054447a3790015b7214d07.

[13] Texas Instruments, *"Bridge Measurements System,"* Precision Analog Applications Seminar, accessed June 15, 2023. [Online]. Available: https://www.ti.com/lit/ml/slyp163/slyp163.pdf?ts=1686592436796.

[14] *"Differential Amplifier,"* Electronics Tutorials, accessed June 15, 2023. [Online]. Available: https://www.electronics-tutorials.ws/opamp/opamp_5.html.

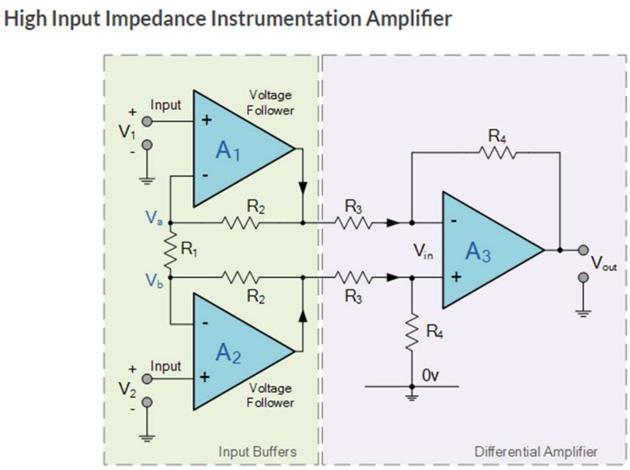
[15] *"HX711 Datasheet,"* Avia Semiconductor, accessed June 15, 2023. [Online]. Available: https://www.digikey.com/htmldatasheets/production/1836471/0/0/1/hx711.html.

[16] T. Reynolds, private communication, June 2023

11 Appendix

11.1 High Input Impedance Instrumentation Amplifier

This information was found during the investigation into strain sensor amplifier options. It did not seem relevant to this report, however it is a useful area of exploration for further study. [14]



$$V_{out} = (V_2 - V_1)\left[1 + \frac{2R_2}{R_1}\right]\left(\frac{R_4}{R_3}\right)$$

Figure 24 - Instrumentation Amplifier [14]

11.2 Calculating Strain for a 1kg mass load

This analysis was intended to be part of the verification and validation, however it did not offer any qualification past the initial calibration and validation test using the 10 N weight.

A test was set up utilising a single truss member hung from a point. A known mass of 1kg was applied to the truss member and the strain value for each channel was reported by the microcontroller using the HX711 Arduino library to convert the electrical signals to a strain value.

In order to validate the results, it is essential to know what the expected result will be. Therefore the expected strain value for a 1G longitudinal loading on the truss member must be calculated.

The dimensions and material properties of the truss member are as follows, taken from the model developed in an earlier report on the truss structure [1]

$l_0 = 0.2\ m$ Member Length

$h_0 = 0.02\ m$ Member Height

$w_0 = 0.008\ m$ Member Width/Thickness

$Ym = 3300\ MPa$ Youngs Modulus/Modulus of Elasticity

Calculate the cross sectional area of the truss member:

$$A_{cs} = h_0 \times w_0$$

$$A_{cs} = 0.02 \times 0.008 = 0.16 \times 10^{-3}\ m^3$$

Calculate force applied by 1kg mass:

$$F_{1kg} = 1 \times 9.81 = 9.81\ ms^{-2}$$

Calculate Stress in member.

$$\varepsilon\ (Nm^{-2}) = \frac{F\ (N)}{A_{cs}\ (m^2)}$$

$$\varepsilon\ (Nm^{-2}) = \frac{9.81}{0.008} \approx 1.23\ kNm^{-2}$$

Calculate expected strain using modulus of elasticity.

$$strain = \frac{\varepsilon\ (Nm^{-2})}{Ym\ (Nm^{-2})}$$

$$strain = \frac{1.23\ kNm^{-2}}{3300\ MNm^{-2}}$$

$$strain = \frac{1230\ Nm^{-2}}{3300 \times 10^6\ Nm^{-2}} = 0.373 \times 10^{-6}$$

Thus the value of 373n will be used as a reference to calibrate the scale