IDT PROJECT
LOGBOOK

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Timeline:
20/01/25 - 17/04/25

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Introduction

This is a working document containing entries logged during project sessions. Workings, component values, results etc. are not necessarily finalized and should not be considered to be so, unless specified. Each session end is denoted by a thin red line. Questions are posed (seen in colourized format), purely to signify thought process and no rough work or errors have been retracted. References and links are all entered in Section 9.1 and compiled in chronological order.

Session One

Wednesday 22nd January

Aim for this session: Gather components and begin building Wheatstone bridge circuit.

First allotted project time begins. Given the tight time schedule today its unlikely any work will commence on the actual circuits etc. The first thing each of the team will do is search for the 3-D printer which will act as the housing and motor control for the entire profilometer.

Multiple different models have been identified, with the only major differences seemingly being the types of motors present in each.
This doesn't affect my portion of the project a great deal but ensuring the correct one is chosen is pertinent for the project as a whole. Regardless of which model is eventually chosen the dimensions will be the dominant constraint for the cantilever.
A 3-D printer has been selected. Now, the following components as listed in *Table 1* need to be found.

Components
Cantilever
4 x Strain Gauges (350Ω)
Power Supply
Instrumentation Amplifier

Table 1: List of Components

Luckily the **INA122P**, the instrumentation amplifier outlined in my proposal, is readily available with multiple replacements for contingency.
Unfortunately, the same can't be said for the linear strain gauges. Having sifted through the stock room it appears as though two **5mm** and two **2mm** (all Radionics models) are all that is available. This poses a question. Can a full bridge configuration be set up with multiple different dimension strain gauges?

It has been brought to my attention that sets of stainless steel rulers have previously been used for separate experimental purposes with similar strain gauges already installed. Two things to note, these may be perfect for testing early set-ups of the circuitry and they may also outline exactly how the contact pads and wires ought to be soldered (a challenge which will shortly arise).

Thursday 23rd January

Aim for this session: Now that components have been gathered, begin construction of the Wheatstone bridge circuit.

Although the plan to produce a full-bridge configuration with the four strain gauges is unchanged, it is decidedly best to first build a quarter-bridge in order to test the workings of the strain gauge and cantilever pairing.

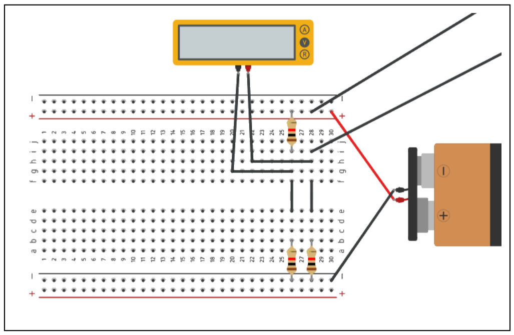


Figure 1: Current Wheatstone Bridge Set-up

As seen in Fig.1, a 9V battery source was initially used to power the bridge circuit. Following an expanded thought process this will be replaced for now by a dual power supply. The battery idea initially stemmed from the thought that prioritizing ergonomics and minimization of the systems scale would be ideal. However, I clearly had not factored in the fact that a NI-DAQ is a necessary component here anyhow and that its **5V output** could be used to power the bridge as well as the amplifier chip. Hence, for the time being, a dual power supply will be utilized with an equivalent output.

With the current set-up, fluctuations are being seen when the ruler (pre-installed with a similar model strain gauge) is placed in the fourth resistor position seen previously. Having said that, initially the fluctuations observed were clearly odd. When the ruler is stressed in a certain manner (i.e. whether force is exerted downward or upward) it seems to make a difference to the result. Polarity of wires ought to be checked. Do strain gauges react differently if stressed in different directions?

Measuring across the bridge, when steady force exerted and stable results return, the voltage change $\mathbf{\Delta V_B = 10 - 20mV}$. Accounting for the fact that the excitation voltage of 5V is contributing here, that indicates a $1 - 2mV$ change between the two two nodes. This is exactly within the expected range predicted before the project began.

Final decision today is to begin setting up the amplifier circuit. While this is undoubtedly premature according to the project Gantt chart, I now believe it to be the best decision. If I were to do any major work in terms of data collection for this rudimentary set-up pre-amplification, any oddity in the amplifier circuit could potentially deem that data unusable.

For future reference, I will be working with the gain equation:

$$\mathbf{G = \frac{200k\Omega}{R_G} + 5}$$

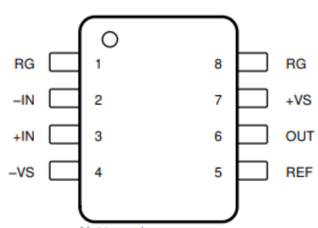


Figure 2: INA122P Pin Diagram

Session Two

Wednesday 29th January

Aim for this session: Set up the Amplifier Circuit and confirm it is functioning

To start session two time was spent assuring that all of my components compiled in the previous session were present. The length of time taken here to gather and sort materials is entirely unsatisfactory. From this point forward organization of the teams storage compartment will require greater care. For reference, nothing is put away at the conclusion of the weekly Wednesday portion, only at the end of the session concluding Thursday at 1300.

Continuing on now from where progress was paused on Thursday 30th. The amplifier circuit is being set up for the first time. The only reference material being used here is the **Texas instruments datasheet** for this amplifier chip, found at:
`https://www.ti.com/lit/ds/symlink/ina122.pdf?ts=1740844143014&ref_url=https%253A%252F%252Fwww.google.com%252F`

The amplifier circuit should fit nicely onto the same breadboard as the Wheatstone bridge circuit. This should allow for a neat integration, of what is essentially this apparatus' entire circuitry, onto the printing rig at a future date. Now, I am aware of the possibility of configuring this amplifier circuit in either a single power supply or dual power supply set-up. After some thought, it is decided that at this current moment a dual power supply is more appropriate. The reason supporting this decision is simply that, though my experience with circuitry is limited, I do have more familiarity with the **dual power supply** amplifier circuits. Not to say that a single power supply circuit would be hard to create but potential unknown issues that may arise risk time mismanagement.
The amplifier circuit is being powered with rails of $\pm \mathbf{5V}$, with no gain resistor initially installed (for natural gain of 5), and the **V_{Ref} left untouched for a null offset**. The circuit now takes the form as seen here in Figure.3. By choosing $\pm 5V$ to power the amplifier, the same power supply can naturally be used to excite the Wheatstone Bridge. This should allow for only one power supply being necessary for the apparatus.

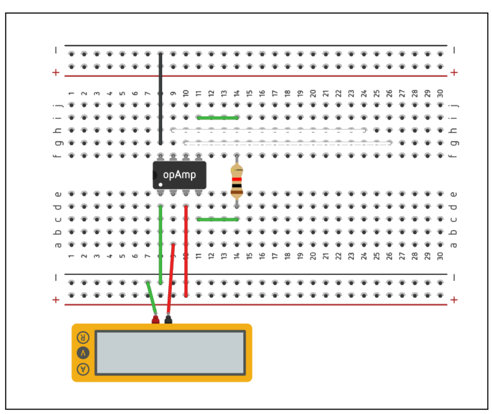


Figure 3: INA122P Pin Diagram

Thursday 30th January

Aim for this session: Confirm Amplifier Circuit works and integrate with Wheatstone Bridge circuit.

Portion two of the second session is now underway. Given that apparatus did not have to be put away after the last session progress can now pick up from where it was left. The amplifier circuit, as seen in Figure 3 is now ready to be tested. In order to do so, the outputs of the bridge seen, in the aforementioned figure as the white wires are connected to the $-\boldsymbol{In}$ & $+\boldsymbol{In}$ nodes.

To remind the reader, we are working currently with a single strain gauge set up on the cantilever. The cantilever is not being hinged on a given surface but for the purpose of rudimentary testing here it will be stressed in a freehand manner. The maximum strain output across the bridge before excitation is $\boldsymbol{\approx \pm 2mV}$. With an initial excitation voltage of $\pm 5V$, an output of $\boldsymbol{\approx \pm 10mV}$ is expected, pre-amplification. Table 2, outlines the outcome of the very first testing of the Bridge and Amplifier circuit working in tandem. This was tested for both the natural gain of the chip, **5**, and the gain with $R_G = 39k\Omega$, giving a gain of **10**.

Excitation V	R_G	**G**	V_out **(No strain)**	V_out **(Strained)**
5V	39kΩ	10	0.60	0.74
5V	N/A	5	0.107	0.125
10V	N/A	5	0.302	0.324
10V	39kΩ	10	0.204	0.251

Table 2: Testing of Bridge & Amplifier

The obvious takeaway from this table is that although applied strain on the ruler mechanism certainly correlated to an increase in the voltage out, the amplifier is clearly not functioning correctly. Where 5V was applied to the bridge and amplifier, the gain of 10 actually returned a lower $\boldsymbol{V_{out}}$ than the supposed gain of 5. The circuit will now be diagnosed for any potential circuitry issues that might be causing these erroneous values.

Upon, further reflection it seems as though the potential issue may have been identified. The INA122P has a $\boldsymbol{V_{Ref}}$ node. As no reference offset voltage was desired here this leg was simply ignored. Having rereads through the instrument datasheet it appears as though this leg, when not in use, has to be grounded. This simple error will now be rectified and the circuit tested again.

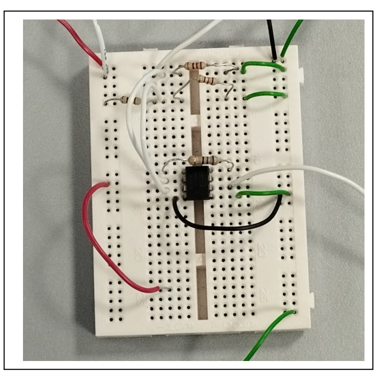


Figure 4: Actual Depiction of Current Circuitry

Session Three

Wednesday 5th February

Aim for this session: To prepare for the integration of the strain gauges onto the ruler.

Session three is now underway. The group is now cognisant that the interim presentation is set for three weeks from now. Though much will be done between now and then we ought to have a set goal to be completed before full preparations for the presentation are made. For this section of the project, ideally, the cantilever will be calibrated by then and an early version of the LabView code may be realized.

Having seemingly rectified the issue that was occurring in the last entry; amplification values appear to be closer to that which was expected (more on this later), there is now a decision to be made. Should a rough calibration of the single strain gauge setup be made? In order to confirm that the setup as a whole is operating in line with expectations. Or, ought the full four-strain gauge setup now be configured? Again, though this may be a hasty choice, it is decided that the latter would best serve the forward progress of the project. That is, the strain gauges will be mounted onto the ruler in a permanent manner and wired into the Wheatstone Bridge.

Some time is taken here in order to organize fully the order in which this process will be carried out. A rough sketch has been made to determine which strain gauges ought to be placed on the top and bottom of the ruler and consequently, what are the optimal positions? It is best to now check in with the team before proceeding. The main topic for discussion here is to determine what length the ruler ought to be, given the physical constraints as ordained by the laser array and raster scanning. Given that the test piece can be manipulated to any size, it will take a secondary role in the hierarchy of importance.

Having conversed with my colleagues, the allowed range for the length of the ruler, from the hinge point located on the extrusion box, is anywhere in the region of $\mathbf{13-19}\boldsymbol{cm}$. Given the permanent nature and valuable time it may take to remove the strain gauges, they will decidedly be placed as far down the ruler (toward the free end) as possible, though maintaining a sufficient spread for wiring considerations. Its worth reminding the reader at this point that the strain gauges available here are split into two different dimensions. There are $\mathbf{2\times 2}\boldsymbol{mm}$ & $\mathbf{2\times 5}\boldsymbol{mm}$ options. Cognisant of the possible fluctuations that may occur in such a setup, they must be arranged in such as way that variations are kept to a minimum. With that, the gauges of equivalent dimension will be located opposite from one another, with the larger variety closer to the hinge point and the smaller toward the free end.

This configuration can be seen as indicated in the sketch in Figure 5.

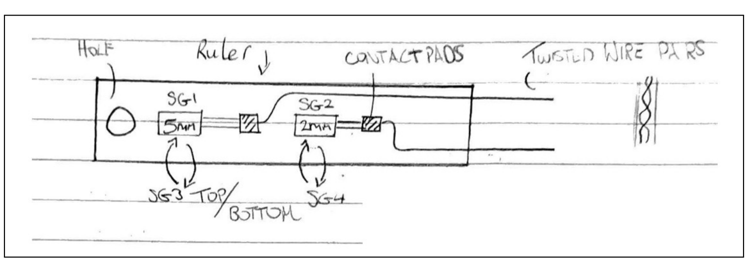


Figure 5: Indication of ruler layout

Thursday 6th February

Aim for this session: Full, permanent integration of the strain gauges onto the ruler and setup as part of the Wheatstone Bridge circuit.
Second portion of session three is now underway. Having outlined the general layout of the apparatus in the previous session, the next step is now physically attaching the strain gauges onto the ruler. In order to this a suitable epoxy. Though the data sheet is vague on this particular matter the RS-Product Details section does specify:

> **Can be affixed with epoxy or cyanoacrylate adhesive**

Noticeably the data sheet for these particular strain gauges never seem to have been entered into the logbook. This should have been done previously, nevertheless it will be entered now for completeness. RS-Pro Low Profile Strain Gauge Datasheet:
`https://docs.rs-online.com/7b45/A7000\protect\penalty\z@00008880707.pdf`

Anyhow, luckily an RS cyanoacrylate adhesive was at hand and so is perfect for use here. Utmost caution is advised when handling these rather fickle little devices and so a tweezers was used for their handling. All barring one of the gauges was attached with relative ease. Having said that the one stand-out of this grouping proved quite stubborn. Though it was eventually attached, I believe it may be possible that one corner is still slightly loose despite all efforts. This should be monitored in the case that future test readings return unusual.
With this complete, the accompanying contact pads are attached. This process proved easy with no a self adhesive installed on the pads. Now that the pads have been placed on the ruler, two wires will need to be **soldered to the pads**, alongside the legs of each of the strain gauges. Having never soldered before, at this point it seems prudent to learn. Using a mixture of Youtube tutorial videos in addition to a quick demonstration by the lab technician should prove sufficient.
Having practised on a few test pieces, this process is finally begun. Though relatively simple, due to operator inexperience the length of time required here proved rather inefficient. However, after needing to return to the soldering iron multiple times due to the legs coming loose, the connections were tested and appear to working successfully.
In order to keep these rather long and ungainly wires in as need a state as possible, they have each been braided into **twisted wire pairs** as was initially suggested in Figure 5. The outcome of this session can be seen below in Figure 6.

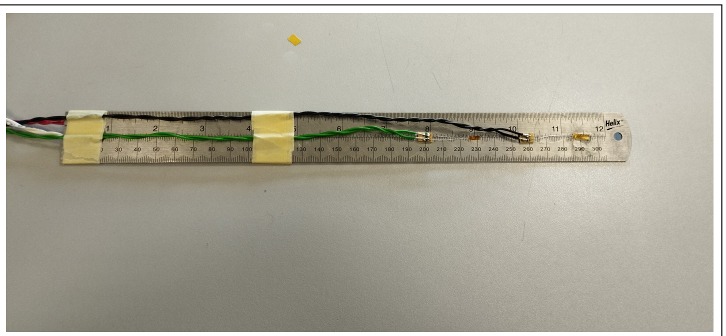


Figure 6: Fully Configured Cantilever

Session Four

Wednesday 12th February

Aim for this session: To prepare and undertake a suitable calibration for the fully formed cantilever.
Session four is now underway. With the fully formed cantilever now at our disposal, the natural next milestone ought to be undertaking an appropriate calibration. Some thought will now be afforded for figuring out the most controlled manner in which this can be carried out. While a direct deflection to voltage calibration would be ideal, I don't believe the necessary increments can be created for greatest accuracy. With that, it is decided that the best way to calibrate this device, under the current conditions, will be via a **mass versus voltage plot.**
Although this may prove a slightly overcomplicated manner, I believe it should return the desired accuracy if done correctly. To begin, the cantilever is mounted onto the edge of the laboratory workbench, hinged at the mark 19cm from the free end.

[It ought to have been noted earlier that the twisted wire pairs have each replaced one of the previous placeholder resistors that occupied the Wheatsone Bridge.]

Now, a known reference load will be required here. The laboratory weights will be used for this purpose as a handy handing device accompanies them. Initially, I was to use the 0-1kg weights, but upon reflection this would correspond to a top load force of almost 10N. A more appropriate calibration range is necessary. Having consulted the technician, a new set of weights, with $\approx 10g$ increments was located. Using this, a **load force range** of $\approx 0 - 1.5N$ can be applied. This ought to be far more suitable for our purpose.
These weights are un-calibrated, as such, each will be weighed individually before use. The **error range** on these mass values is $\pm 0.001g$, which will be noted for later analysis. Additionally, for greatest accuracy, a **TTi5$\frac{1}{2}$ digit DMM** was procured for greater accuracy in voltage measurements here.
Before calibration begins (this will occur in the next portion of session three due to time consideration), the amplifier circuit will now be reconfigured. According to the Texas Instruments datasheet, this instrumentation amplifier can be suitably utilized in a **single power supply setup**. My thinking here is that with a single power supply arrangement this could potentially unburden the necessitation of a dual power supply and potentially allow for the use of the NI-DAQ to power the circuit. To do this, a slight amendment was made to the circuit.
The V_- was grounded, along with the $Vref$ and a **$0.1\mu F$ bypass capacitor** was added between V_+ and ground as per the suggestion in the datasheet:

> **Connect low-ESR, 0.1µF ceramic bypass capacitors between each supply pin and ground, placed as close to the device as possible. A single bypass capacitor from V+ to ground is applicable for single-supply applications.**

Seen below in Figure 7 is the current state of the apparatus, in preparation for the calibration sequence.

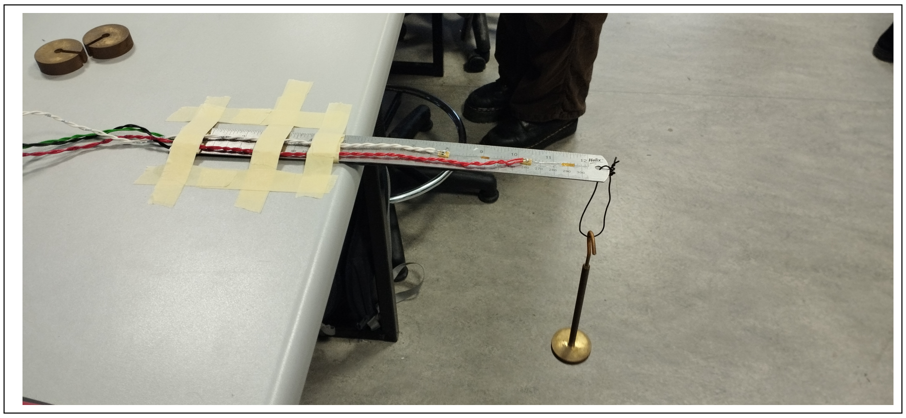


Figure 7: Fully Configured Cantilever

Thursday 13th February

Aim for this session: Complete the calibration of the cantilever, produce a calibration equation and potentially begin the accompanying LabView code.

The second portion of session four is now underway. Two calibration tables will be produced here, the first will be an unamplified version and the second will be after a G=5 amplification. This will be done to ensure as observations of the amplified values to begin this session have been seemingly off. Should the output appear unlikely, the circuit will be returned to for further investigation. Could the single power supply have thrown off the amplifier functionality? It's certainly a possibility. Either way, once the calibration data has been produced, they will be plotted against each other in Python for an observation of the relationship.

Mass Added (g)	Force (N)	Bridge Voltage (mV)
0	0	1.033
10.55	0.1035	1.075
20.64	0.2025	1.113
30.67	0.3031	1.152
40.69	0.3991	1.192
50.70	0.4974	1.231
60.71	0.5956	1.232
70.67	0.6933	1.311
80.65	0.7912	1.349
90.32	0.8999	1.386
100.35	0.9987	1.427
110.85	1.087	1.467

Table 3: Calibration Table (No Gain)

Mass Added (g)	Force (N)	Output Voltage (mV)
0	0	15.074
10.55	0.1035	15.285
20.64	0.2025	15.515
30.67	0.3031	15.745
40.69	0.3991	15.981
50.70	0.4974	16.226
60.71	0.5956	16.473
70.67	0.6933	16.702
80.65	0.7912	16.967
90.72	0.8999	17.202
100.79	0.9987	17.445
110.85	1.087	17.720
120.95	1.186	18.042
131.09	1.287	18.367
141.20	1.385	18.692
151.32	1.484	19.015
161.40	1.582	19.341
171.57	1.681	19.670
181.75	1.780	20.031
191.84	1.879	20.335
201.90	1.977	20.666

Table 4: Extended Calibration Table (Gain = 5)

With an excitation voltage of 5V across the bridge and a **natural amplifier gain of 5** (i.e. no $\boldsymbol{R_G}$ present) these outputted voltage values seen in Table 4 are clearly inaccurate. Given that the bridge output values appearing in Table 3 are exactly within the expected value range, troubleshooting should simplify here. The issue is very likely stemming from the amplifier circuit. This will now be double checked for misconfiguration.

Having spent quite some time checking for errors here, a great difficulty is experienced in diagnosing the issue. Logically speaking, given that no issues with amplification were observed prior to the reconfiguration of the circuit into single-supply mode, that must be where the problem arises. However, consulting the instrument datasheet and drawing comparison to the recommended circuitry guidelines outlined there, no error can be readily proposed. Though stubborn instincts do not want to revert to a dual power supply just yet, it may be necessary for progress to resume. As the end of the session is approaching, this will not be carried out today, rather a start will be made to set up a reusable **Python code for plotting and fitting** the calibration data. Easily manipulated code is preferable here (as anywhere of course) as the calibration may need to be repeated a number of times. This will be completed before the next session.

Session Five

Wednesday 19th February

Aim for this session: To find a solution to the amplifier gain issue and complete calibration.

Session five is now underway. The first thing to note here is that the interim project presentation takes place after the next session [Thursday 20th February - 4pm]. Work on slides has been in progress over the previous few days and the team is rather coordinated on the matter. Time will be taken over the next day or so, likely after the next session, to run through the presentation and ensure that the team can perform in a cohesive manner. Continuing on with the work at hand now. As mentioned at the very end of the last session, a Python script for plotting the calibration values was being formulated between then and now. This was completed and a calibration curve for the data obtained in **Table 4**. Though the gain did not appear to be correct here, I don't believe the offset value should cause too much disturbance. If that proves not to be the case, this can very easily be repeated for new data. A linear regression fitting was then utilized to obtain the calibration equation for this data. As seen in Figure 8 below.

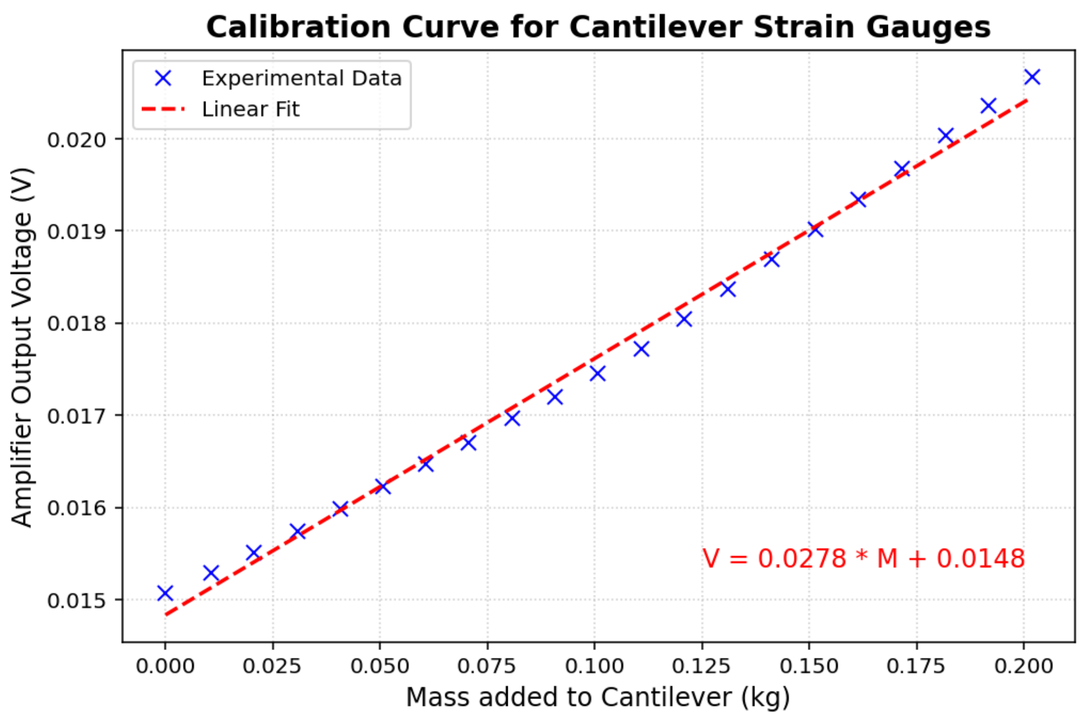


Figure 8: Fully Configured Cantilever

Perhaps a glaring assignment that has gone unmentioned thus far is the fact that this calibration tracks Mass versus Voltage and that no method of manipulation for deflection has been suggested. Given the short nature of the Wednesday sessions, it is decided that time will be put aside in this portion of session five to figure out this vital relationship. Firstly, I will outline the calculations I have just completed below: The relationship between **mass (m) and voltage** (V_0) from the calibration curve is:

$$\boldsymbol{V_0 = 0.0278M + 0.0148}$$

where:

- m is the mass (kg)
- V_0 is the measured voltage (V)

The deflection δ is given by the following formula, utilized for a cantilever with a hinged point at one extremity and the other extremity free to move:

$$\boldsymbol{\delta = \frac{FL^3}{3EI}}$$

where:

- F = force
- L = cantilever length
- E = Young's modulus
- I = moment of inertia

For stainless steel:

$$E \approx 190 \times 10^9 \text{ Pa}$$

$$L = 19 \text{ cm} \pm 5 \text{ cm} = 0.19 \text{ m}$$

The moment of inertia I for a rectangular cross-section is given by:

$$I = \frac{bh^3}{12}$$

Given dimensions:

$$h = 1.05 \text{ mm} = 0.00105 \text{ m}$$

$$b = 29.3 \text{ mm} = 0.0293 \text{ m}$$

$$I = \frac{(0.0293)(0.00105)^3}{12}$$

$$I = 2.8101 \times 10^{-12} \text{ m}^4$$

The constant in the deflection formula:

$$\frac{3EI}{L^3} = \frac{3(190 \times 10^9)(2.8101 \times 10^{-12})}{(0.19)^3}$$

$$= 4.28 \times 10^{-3}$$

Thus, the deflection is:

$$\delta = CF$$

where:

$$F = Mg = 9.81 * (\text{mass in kg})$$

Altogether, the un-calibrated relationship between the deflection and voltage output is:

$$\boldsymbol{\delta} = \frac{CgV_0}{0.0278} - 0.0148 = \mathbf{1.510}\boldsymbol{V_0} - \mathbf{0.0148}$$

We now have a wonderfully simple and workable calibration. Should it be the case that a new equation is necessary when the amplifier issue is nullified, then the foundations for creating a new one have been layed, and re-figuring these will not prove to be a difficult job.

Thursday 20th February

Aim for this session: To create a working LabView to implement the calibration equation and begin initial tests for accuracy. Integration of cantilever onto the main housing structure. [Additional Note: Finalize preparation for Interim Presentation]

The second portion of session six is now underway. Having left off in the last session with a proposed calibration equation the first action of the day will be to conduct initial tests for accuracy. Time will now be taken to determine the best manner in which to test these heights. Having conferred with colleagues, a point was made that the z-motor calibration is now complete. Hence, if the cantilever was mounted into its proposed final position atop the extruder box, the known increments of the z-axis motor could potentially be used to test very specific height variances. This is decidedly the best way to proceed.
Mounting the cantilever is a slightly trickier objective than previously considered, given the extremely restrictive space available on the printing structure. It appears as though the ruler will need to be mounted at the point **13cm from the free end**. This was always a possibility and will only change the constant C value in our calibration. This will be corrected shortly.
The first attempt at working with this newly formed setup is purely to assure that the dimensions are now suitable, and that no extra issues occur as a consequence of the new arrangement. For now, a screwdriver has been affixed to the free end, acting as a temporary place holder for the tip. The current idea for a more permanent replacement is to sever the end of a standard plasticine pen and mount it via an epoxy to the ruler.
Before testing via the aforementioned z-motor method, a conversion with a supervisor indicates a possible cause of the gain issue in the amplifier circuit. It was pointed out that although the datasheet clearly displays and promotes the single power supply configuration of the INA122P, they are often unsubstantiated claims. Taking this advice on board, the circuit will now be reverted to the **dual power supply setup** as witnessed in previous sessions.
With the dual power supply now in place, a quick test of bridge ouput verses gains is made:

Bridge ΔmV	Gain	Amp. Out mV
0.585	5	25.150
-	10	6.83
-	50	30.42
-	100	55.58

Table 5: Unstrained Amplified Output Testing

Deflection $\delta(mm)$	$V_{out}(mV)$
0	212.322
5	31.907
10	-143.100
15	-275.112

Table 6: Integrated Calibration Test

What is clear from this quick test is that the gain of where, where no gain resister is present, returns an odd amplification value. Something is clearly not right here, though that isn't of particular importance in these circumstances. What is of greatest note is that the amplification values from **G=10** and upward appear to be valid. With this in mind, it is decided that the **G=100** option will remain constant on an ongoing basis and will not be altered unless otherwise stated. Hopefully, this issue has been laid to rest.

Continuing now with a quick test to check whether the z-axis motor can be used to recalibrate our device. The cantilever is lowered such that the tip is in contact with the surface of the printer stage but no unnecessary force is applied. The device will lower in **increments of 5mm**, deflecting the cantilever upwards.The following table results:

Unfortunately, the method has proved unviable. The z-axis motor simply did not have enough torque (or perhaps was not afforded enough power under the conditions?) to exert any more downward force than is seen in **Table 6**. What is relevant here is the fact that deflection appears to be tracking uniformly to the voltage output. In addition, positive deflection is equating to a negative voltage, as such the polarity of the calibration equation will need to be flipped in LabView (minor note). The LabView code is not organized as it appears below in Figure 9, with the ouput in centimetres of greatest relevance to the user given the small increments involved here. Final preparations will now begin for the IDT Interim Presentation portion of the overall assessment. A slide deck has been arranged and the group will convene to attempt several trial runs before the event.

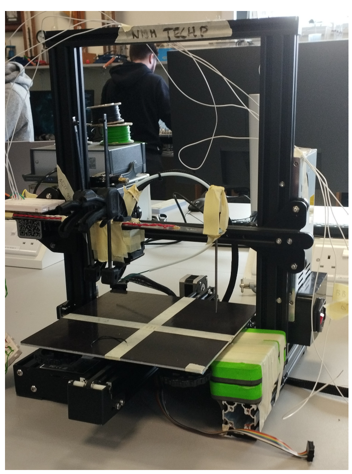


Figure 9: Current State of the Integrated Apparatus

Session Six

Wednesday 26th February

Aim for this session: To implement a digital tare and make more permanent the manner in which the instrument is fixed to the extruder box.

The sixth session of this project is now underway. A quick note to begin here is that seen in Figure 9, the eagle eyed viewer may have picked up on the fact that an amendment to the printer housing has been made. Having searched for a possible way to conjoin the cantilever to the extruder box, a pair of portable (and thus lightweight) vice clamps were found. These significantly improved the force with which the cantilever is fixed to the z-axis beam (extruder box). Which in turn increases the accuracy of the hinge point of the cantilever, previously the ruler was seen to lift ever so slightly when force was applied at the free end. This solution should be viable to maintain for the duration of the project.
The breadboard, attached to the cantilever via the four twisted-wire pairs, necessitates a close proximity to one another, due to the length of the wires. Thankfully, the current wires appear to be long enough, with some extra contingency length, for this purpose. This breadbaord has for the moment been attached to the left hand side of the printer housings base (as seen viewed from the angle in Figure 9).
Unfortunately, on the first attempt the returned value for deflection (no physical deflection imposed) did not align with expectation. While a renewed effort calibration-wise will be neccessary, what is also evident is that a digital tare will required in order to return truly accurate readings. Up until this point in the project, the offset, as seen appearing in the deflection calibration equation, served this purpose. This will not suffice. Instead, due to obvious disturbance and variation in the starting value of the circuit, the tare must allow for an evolving initial value.
Creating such a mechanism within my LabView code should have been quite simple. However, without elaborating too much on this statement, this was not the case here. Primarily due to inexperience with the finer details of LabView's workings. Figure 10 below depicts the current state of the LabView script after a rather long period tinkering with the many possible avenues of approach. A true/-false block serves as the foundation for this mechanism. Wired to the true, is the current value of the output voltage. Wired to the false, is the read function of the 'Tare Value' local variable. The output of the block is the write version of the same local variable. The block is then activated by a Boolean push button. When the button is pushed, the output voltage is triggered here, this is then written the local variable. The reading version of the local variable then keeps track of this value. Note, is the push button isn't switched off again, it will continue to write a moving value to the read variable, resulting in a constant null output. Instead, the latch mechanism is utilized, meaning in essence, the button is switched on and off in the same instance.
Though that is perhaps a slight bit confusing in writing, it becomes more clear when viewed in its entirety in Figure 10. The 'read' local variable is then subtracted from the voltage output. On first activation, this should result in a 0cm deflection value. By the end of this period the tare is seen to be working successfully.

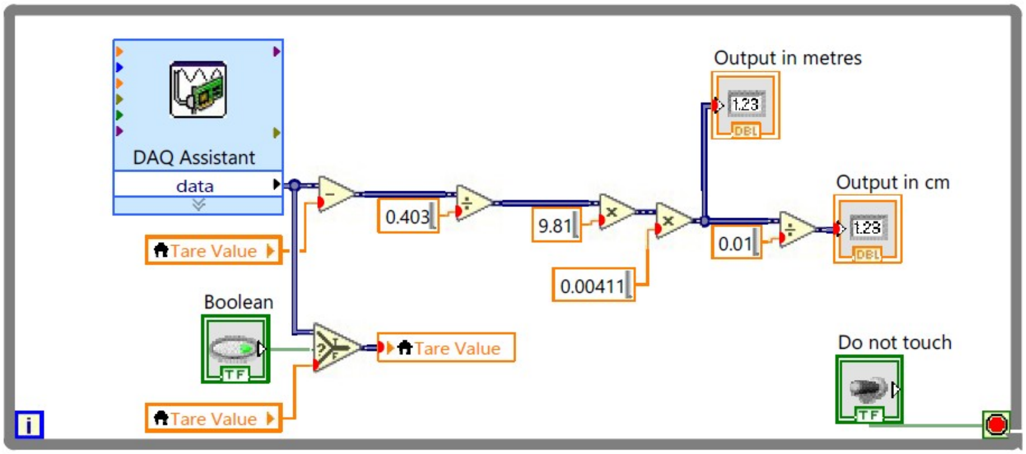


Figure 10: Tare mechanism implemented in LabView

Thursday 27th February

Aim for this session: Integrating the z-motor and cantilever functionality.

The second portion of the sixth session is now underway. The digital tare took a regrettable chunk of time considering the final product, though its functionality is undoubtedly vital the end goal of the device. Given the short length of time left before the termination of the project, the overarching plan dictates that attention must now turn to the integration of individual apparatus. In my case, the first port of call is to figure out when my digital tare must be enacted. With regard to the rest of the group, my colleague Niall's work on the z-axis motor will play an important role in this decision.
To quickly recap, the z-axis motor will be triggered to travel downward at the start of each new scan. This will continue until the slightest deflection of the cantilever, moves the laser (angled onto the back of the cantilever) upward onto the photodiode array and forces the z-motor to cease its operation. Taking all of this into consideration, the same voltage that triggers that operation to stop, could be used to trigger my codes tare.
Having verified that Niall's code reacts appropriately to the laser impinging on the photodiode, the LabView script can now be amalgamated in some manner. Much of this work will not be outlined in detail here but a simple overview will be provided. The first attempt at combining the two codes, followed an unorthodox and unadvisable method. My code was simply copy and pasted into Niall's VI and his threshold voltage was utilized in attempt to trigger the tare to occur. In short an unworkable issue cropped up in this scenario. The two while loops were not running in a synchronous manner. Instead the original loop ran first, without a regard for the latterly added loop. This occurred due to Labview's habit to treat the code in a top-left to bottom-right read pattern (this might need to be double checked but that is the understanding from initial observations).
Conversation ensues on the best option going forward. It has been decided that a stacked structure ought to be created. With the z-axis motor appearing first in the sequence, the tare is then turned on, then subsequently turned off and finally the original calibrated voltage output to deflection code is positioned in a for loop, repeating for a given number of iterations. This code took some finicky configuration, though appears to be working at a rea-

sonable level, returning values of deflection at the very least.

Having said this, the values for deflection seem to be entirely unlike those that had been seen previously. Previously, the deflection were on a correct magnitude scale if still incorrect, though now the deflections are in metre range. What has changed since the last measurements were taken? Troubleshooting of the circuitry will now begin.

Unfortunately, disassembling the entire cantilever was required, and a fine combing of the circuit ensued. As of yet no issue can be identified. Retracing the assembly points, stripping back each component one by one, seemingly introduced more questions than it answered. Right back to the resistance across the legs of each strain gauge, everything appeared in order, though odd values across the bridge continue to appear. With time elapsed for session six, this investigation will have to continue into session seven. Concious of the deadline approaching, should this problem be insurmountable in the next session, the contingency of reverting to a single strain gauge setup exists. This would be rather demoralising, but for the greater good in the context of the entire project, may possibly prove the only viable option.

Session Seven

Wednesday 5th March

Aim for this session: Troubleshoot remaining issues and set up the model in working condition for final testing in the next session.

To reiterate the problems which arose in the last session, the values across the bridge and thus out of the amplifier circuit have become erratic. Stripping back the circuitry hasn't revealed the exact root cause. Having said this, the major implication here is that the full bridge configuration of the Wheatstone bridge is currently infeasible.
Thankfully, the manner in which the device was developed allows for the easy transformation of the number of strain gauges being employed. Testing will now commence on the other configurations, wherein a lesser number of strain gauges are wired into the Wheatstone bridge.
After a number of trials, checking for levels of stability by monitoring voltage outputs in response to uniform increases in applied force values. The results here were conclusive. While the single strain gauge configuration was noticeably stable, the half bridge configuration was by far the most effective of those tested.
Going forward with the half-bridge configuration now necessitates the completion of a new calibration. The same calibration method as previously outlined, wherein mass is added to the end of cantilever and the corresponding voltage output is recorded. The results of this new calibration can be seen below in Figure 11 and table 7 below. The resulting calibration equation as extracted from the linear fitting is as follows:

$$V = (0.1036 \pm 0.001)F + (2.7818 \pm 0.006)$$

Mass (g)	Voltage (V)
0	2.788
100	2.887
200	2.996
300	3.075
400	3.178
500	3.279
600	3.390
700	3.494
800	3.610

Table 7: Mass added to cantilever vs. amplified bridge output voltage.

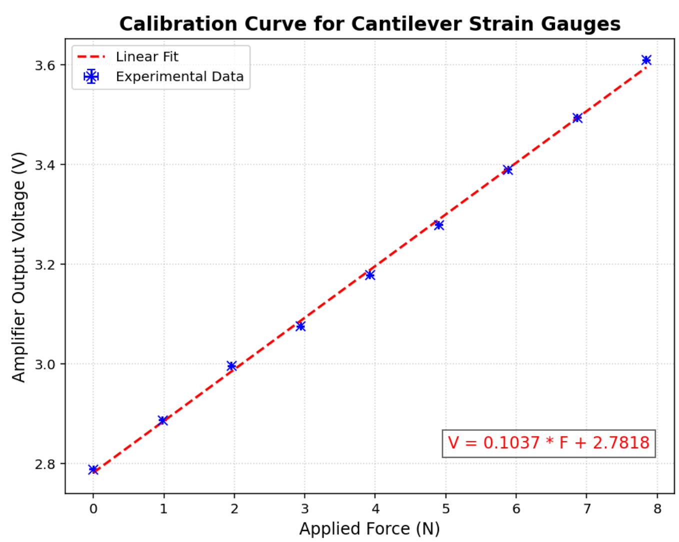


Figure 11: Calibration curve, corresponding to data seen in Table 7 - showing relationship between output voltage versus Force

Thursday 6th March

Aim for this session: To complete error analysis and begin initial height tests.

The first process carried out today will be some quick calculations for the error propagation necessary here. These can be seen below:

This calibration should now be suitable to be implemented into the LabView. With this, the device should be appropriately setup for further testing tomorrow. Given a mass measurement uncertainty of $\pm 0.5\,g$, the force uncertainty is:

$$\Delta F = \Delta m \cdot g$$

DMM Uncertainty
For the DMM used here the following specification apply:

$$\text{Accuracy} = 0.02\%, \quad \text{Resolution} = 1\mu V$$

Total voltage uncertainty:

$$\Delta V = 0.02V + \text{Resolution}$$

$$\Delta V = 0.02V + 1 \times 10^{-6}V$$

Revised Calibration Equation
Applying the above uncertainties to the Python plotting script for the calibration values, the following revision of the calibration equation is computed:

$$\boxed{V = (0.1036 \pm 0.001)F + (2.7818 \pm 0.006)}$$

Deflection Equation

The deflection of a cantilever beam under a force F at length L is as previously stated in Equation 5:

$$\delta = \frac{FL^3}{3EI}$$

Uncertainties in the parameters contribute to the total uncertainty. Given the length of the following equations, a wide format will temporarily be utilized:

$$\frac{\Delta\delta}{\delta} = \sqrt{\left(\frac{\Delta F}{F}\right)^2 + 9\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta E}{E}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \tag{1}$$

With given values:

$$\Delta F = 4.9 \times 10^{-3}N, \quad \Delta L = 1 \times 10^{-3}m, \quad \Delta E = 2\% \times 190 \text{ GPa}$$

Inertial Moment
Before continuing Equation 6, we must first examine the final term, which represents the relative uncertainty in the moment of inertia. As known from Section 1.2, this requires further propagation. Using the equation for the moment of inertia and the recorded values with associated uncertainties:

$$I = \frac{bh^3}{12}.$$

$$\Delta h = 1.05 \text{ mm} \pm 1 \times 10^{-2} \text{ mm}, \quad \Delta b = 29.13 \text{ mm} \pm 1 \times 10^{-2} \text{ mm}$$

$$\frac{\Delta I}{I} = \sqrt{\left(\frac{0.02 \text{ mm}}{29.13 \text{ mm}}\right)^2 + 9\left(\frac{0.03 \text{ mm}}{1.05 \text{ mm}}\right)^2}$$

$$\boxed{\frac{\Delta I}{I} = 9.579 \times 10^{-4}}$$

Averaging Values Approach
Since force varies continuously, an averaging approach is employed to reduce large relative errors for small force values. The mean of the force values is calculated as:

$$F_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N} F_i \tag{2}$$

Deflection is then calculated using the F_{avg} value, obtained from the dataset and given as $F_{\text{avg}} = 3.92N$:

$$\delta_{\text{avg}} = \frac{F_{\text{avg}} L^3}{3EI}$$

$$= \frac{(3.92N)(0.13m^3)}{3(190 \times 10^9)(2.81 \times 10^{-12})}$$

$$\delta_{\text{avg}} = 5.38 \text{ mm}$$

Final Deflection Uncertainty

$$\frac{\Delta\delta}{\delta} = \sqrt{\left(\frac{4.9 \times 10^{-3}N}{3.92N}\right)^2 + 9\left(\frac{1 \times 10^{-3}m}{0.130m}\right)^2 + \left(\frac{2\% \times 190 \text{ GPa}}{190 \text{ GPa}}\right)^2 + (9.579 \times 10^{-4})^2}$$

$$\boxed{\frac{\Delta\delta}{\delta} = 0.088 = 8.8\%}$$

Output Testing

Given the completion of a seemingly satisfactory calibration and the production of the Equation 6, the calibration equation, preliminary testing of the deflection outputs was decided upon. These tests served as rudimentary guidelines for the accuracy of the cantilever readings, primarily intended to indicate whether overall integrated system tests could commence. As such the data sets were brief in depth and rigour. Nevertheless their inclusion here ought to justify the accuracy of the cali-

bration equation seen previously.
The 'true' height increments in question, were that of a simple 3D printed set of stairs with step heights of 0.3cm up to a total Z height of 1.5cm. The distinction between the results in 'Deflection 1' versus those in 'Deflection 2' is that the former utilized the standard Equation 6 calibration value. In contrast, the latter of the two headings utilized a value of double the stated calibration equation.
This result is damning of the calibration equation in the sense that its closest percentage difference was that of 65.47% in comparison with the doubled values optimum percentage difference value of 9.67%. Though an unfortunate finding, it highlights the misbehaviour of the original calibration and had time allowed within the boundaries of this reports submsission, would have allowed for a fresh attempt with a result in the region of $V = (0.20 - 0.30)F$ expected.

Increment (cm)	Voltage(V)	Post Tare	Deflection 1(cm)	Deflection 2 (cm)
0.0	2.746	0	0.000	0.000
0.3	2.614	-0.132	0.545	0.271
0.6	2.496	-0.250	1.032	0.513
0.9	2.360	-0.386	1.594	0.793
1.2	2.254	-0.492	2.032	1.010
1.5	2.145	-0.601	2.482	1.235

Table 8: Experimental data with percentage differences.

With the completion of this testing, the calibration equation has been altered in the aforementioned manner. The penultimate session has now come to a close, the final session will hopefully return a digital topographical output of the chosen object.

Session Eight

Wednesday 12th March

Aim for this session: To ensure that every detail of the integrated device is fully functioning and that appropriate preparation has been made for the bench presentation.

The first portion of the final session of this project is now under way. With the devices new calibration hopefully representative of a more accurate attempt, the cantilever device is now in its final form. The majority of this lab session will be dedicated to the important process of ensuring that the LabView code is working properly. While this had been completed to a certain extent previously, the amalgamation of coding scripts bring with it the many complications of LabView.
The current issue being troubleshooted is the attempted concurrent running of the XY raster scanning procedure at the same time as the height measurement extraction. SubVI's have been removed from this iteration, as it appears as though LabView is attempting to run them to completion before taking height measurements.
Now that SubVI's have been removed the code seems to be running without issue. heights are now being appended to Excel files sequentially by utilizing the 'Write to Measurement File'. The next step now is to attempt a full scanning process. The test piece being scanned here was chosen for its gentle slopes in all directions, which the cantilever device should be more than capable of traversing. A sample display of the test piece can be seen below in Figure 12.

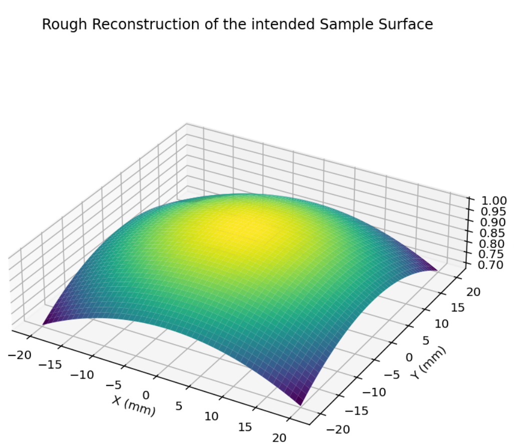
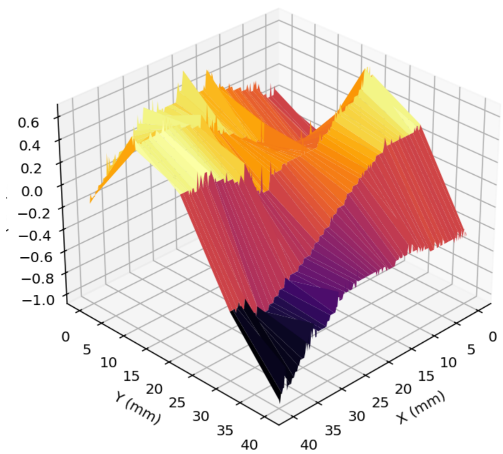


Figure 12: The graphical reconstruction of the test piece used for comparison with produced plots seen in Figure 6.

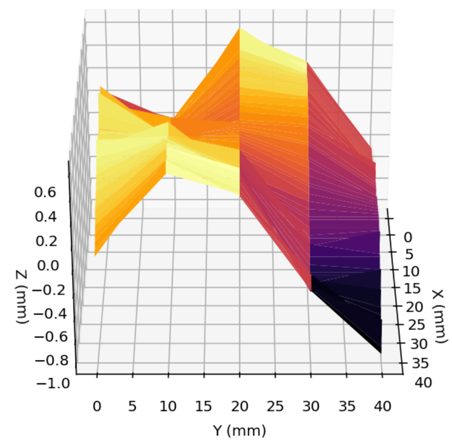
After a short time attempting to fix the laser-threshold voltage mechanism, for stopping the motion of the z-axis motor, the process can now be initiated. The data collected here is displayed as seen in below in Figure 13. The dimensions of the surface are $40mm^2$ with 5 reversals of x-direction in the raster scanning pattern. The heights, originally compiled into an Excel file from LabView, were then converted to a .csv file for easier use in plotting.

X and Y arrays were then readjusted lengthwise in order to appropriately match the length if the Z-height array.

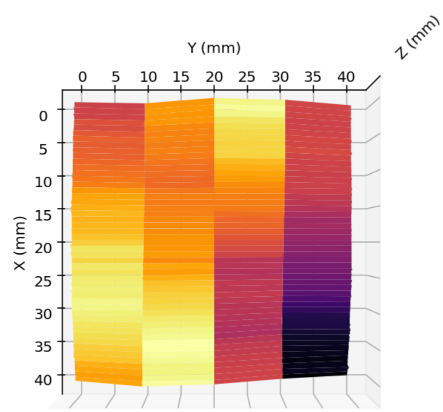
The surface profile as produced by the system testing can be observed from multiple differing perspectives. Readily apparent is the ungainliness of the reproduction, though the relative displacement suggests that with greater testing and troubleshooting, far greater accuracy may yet be achieved with this device. Multiple factors may have induced such noise and variability which will be addressed in the accompanying Report.



(a) 45° X-Y View



(b) Elevated Y-Plane View



(c) Top Down View

Figure 13: Different Perspective Views of the System

Thursday 13th March

This portion of the final session was dedicated entriely to the preparation of the device for the bench presentation, scheduled for later in the day. It is advised that the reader refers to the accompanying report.