Executive Summary

XXXXXXXXXX Ltd (herein noted as “The Company”) are a local interior fit-out company, carrying out a range of internal construction services including, partition walls, ceilings, flooring, passive fire stopping and fire doors, hygienic wall claddings, and acoustic treatments.

Serving the commercial sector, many job sites are large factories, warehouses, schools and office spaces. Unfortunately, many clients do not have any suitable designs or plans, which makes cost estimating difficult. In addition to this, many of the spaces are large and inaccessible making any measured survey impossible.

As such, the inherent design risk is borne by The Company, as they are deemed to have allowed for everything unless explicitly omitted. This risk is mitigated by allowing for a ‘worst-case-scenario’, which often results in inflated costs and wasted materials.

Current estimates note that the interior fit-out industry alone is responsible for about 300 tons of wate going to landfill every day. [ref 3] Therefore, having precise measurements allows for accurate material ordering, greatly reducing the amount of waste generated on site.

This reduction in waste materials and the in-built wasted energy in transporting the materials is how the project fits into the sustainability theme.

The company requires a way to accurately and quickly carry out fully measured surveys of expansive areas for a relatively low cost. This project aims to create a 3D scanner able to accurately survey large, inaccessible spaces in a short time.

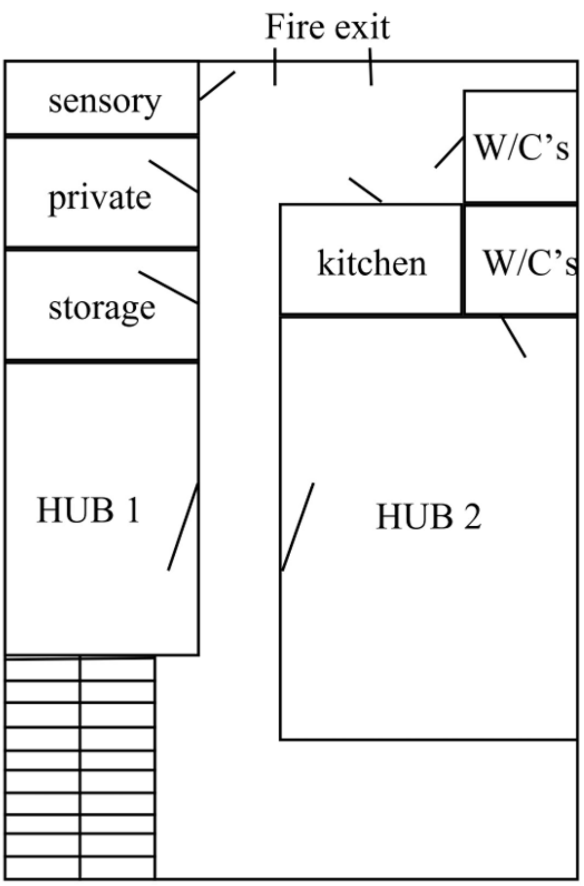
Contents

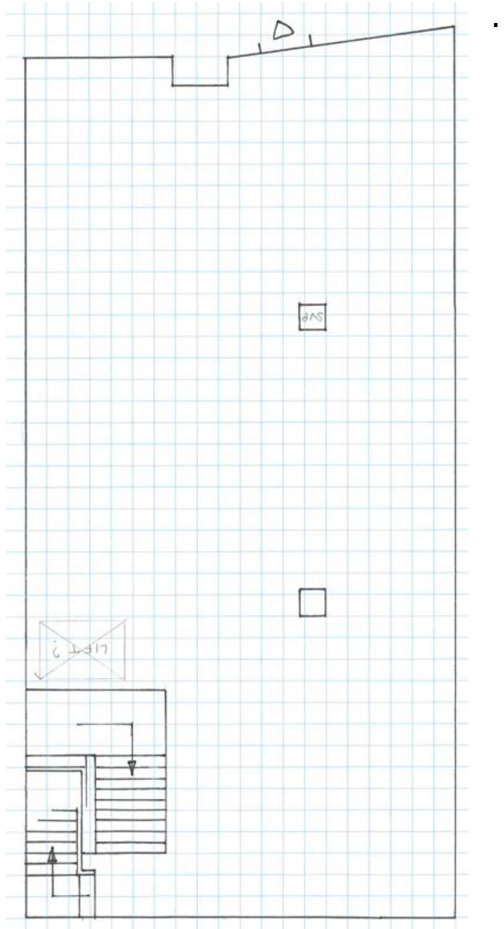
Introduction

The incoming job leads to the company are split in to two main sectors where they are either a main contractor or a sub-contractor. Typically, for the latter, the main contractor will supply the company with a specification of works and scaled, dimensioned drawings to base the price off.

The second sector is where the company is approached directly by the client, where they do not have the technical knowledge or competencies to produce a specification and/or scaled drawings.

Below are examples of client sketch against the actual surveyed floor plan.





As you can see, the proportions of the client's sketch are incorrect and do not represent the actual space. In addition to this, they have completely missed the two structural columns that impede their design!

There are current market solutions with 3D scanners being commercially available items. However, they are expensive with the Leica MS60 R2000 MultiStation costing in excess of £35,000. [ref 4]

This project is meant as a research and development task to produce a single unit for exclusive use by the company – it is not meant for future production or sale.

While this project is being done to benefit the company, they are not funding the works, therefore budget-conscious decisions must be made throughout.
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Project Design Specification

Product Dimensions

The company completed a 16 point dimension sheet to provide the high-level details and outline specifications for the proposed 3D scanner.

Ref	Dimension	Customer Voice	Requirement
1	Functionality – What it should do	Device should be able to non-intrusively survey a room; accurately and fast	Minimum tolerance for accuracy is ±100mm over 20m range. Maximum time for a single scan to be no greater than 15mins. Ideally less.
2	Environmental conditions	All surveys will be carried out internally: no wet. Working temperature will be 0-30°C	No IP rating is necessary.
3	Size	Device should be portable – easily liftable by one person, including tripod.	To fit on the tripod, the device should ideally not exceed 300mm cube.
4	Weight		Ideally, weight not to exceed 10kg.
5	Aesthetics	Not important: function over form.	No exposed wires or mechanisms.
6	Ergonomics	Simple user interface.	User interface to be intuitive, informative and easy to use.
7	Reliability	Should be able to do multiple scans without problem.	Have a fault-free and repeatable process. No wear on parts.
8	Maintainability	N/A	No user-serviceable parts
9	Manufacturability	N/A	One-off unit; not intended for mass manufacture.
10	Recyclability	N/A	Where possible; pre-made sensors to be utilised.
11	Compatibility	Must fit on a standard surveyor's tripod. No digital system in place; therefore, no compatibility	Hardware: Device should fit a standard surveyor's tripod. Software: point cloud output to SD card for easy transfer.
12	Efficiency	Able to work under battery power for a minimum of two scans.	Power consumption to be as low as possible to increase battery time.
13	Cost	As cheap as possible.	A fair estimate for materials is <£1,000.
14	Ethics (Compliancy & Legal)	Comply with necessary legislation.	Laser range finder is class 1 = safe. Laser pointer is class 3a = avoid direct exposure; do not view with optics.
15	Disposal	To be disposed of in accordance with all laws. Recycled where possible.	Batteries to be recycled in a safe and environmentally correct manner.
16	Sustainability (Pearson set theme)	The device aims to reduce the amount of waste produced during building projects by accurately surveying the site.	

Feasibility Study

A feasibility study was undertaken to look at various aspects such as:

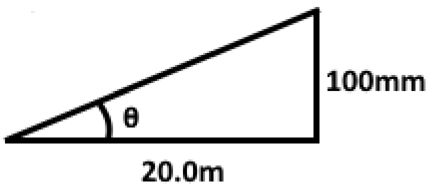
- Technical
- Economical
- Legal
- Operational
- Scheduling

From the study, it was found that the greatest risk was from the scheduling requirements because the whole project will have to be designed and built outside of work and college hours, leaving only evenings and weekends.

The economical and technical feasibility studies also highlighted potential difficulties throughout the project, but these weren't deemed a high risk.

Product Design Specification Summary

Attaining the technical requirements will be a challenge for the project. Using trigonometry, we can see that the angular resolution required to measure 100mm at 20m is 0.29°, as shown with the below calculations:



$$\theta = tan^{-1}\left(\frac{0.1}{20.0}\right) = 0.29°$$

As this project is for research and development, there is a greater degree of flexibility in the design. In addition to this, there are currently no existing IT or CAD systems that this scanner needs to integrate with.

Not having an IP rating means that there is no explicit need for an external casing. Similarly, there is also no requirement for testing or certification from any internal departments or external third-party bodies.

Irregardless of this, the scanner should still comply with all current health and safety laws, and not pose any hazards to the user or any other people in the vicinity.

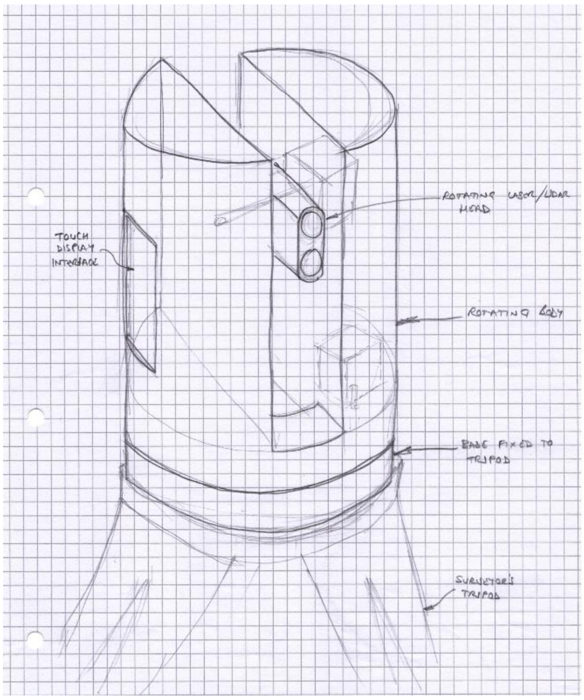
A cost budget of £1,000 does not give much financial head room for experimentation.

Initial Concept Designs & Design Selection

Three initial high-level designs were produced and subsequently tested against the product design specification.

Option 1: Standard Layout

The first option was similar to existing design solutions on the market, utilising a base fixed on a tripod able to rotate about its centre, while also having a perpendicular rotating head where the sensors are mounted.



To solve a problem faced with current market solutions with the inability to aim the sensor straight down, the base of the scanner is to be a toroid shape, allowing the sensor to take a plumb measurement.

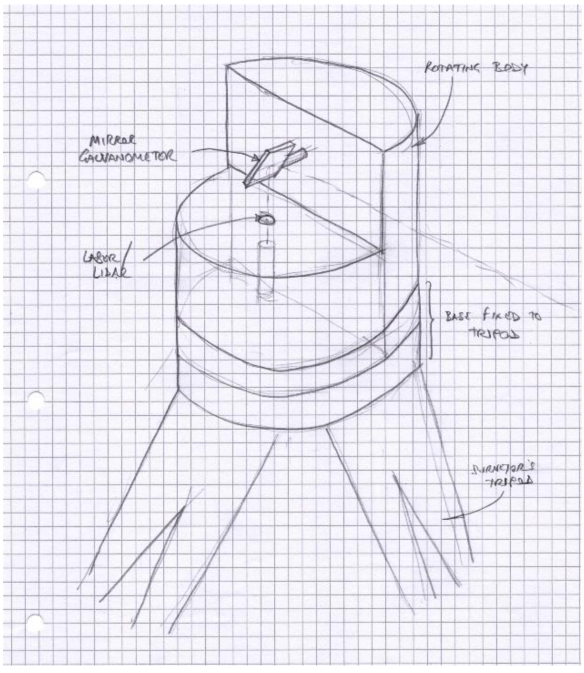
The greatest advantage to this solution is that it is a tried and tested design platform, based on the layout of some existing scanners and surveying total stations. An additional positive point for this design is the mathematics required to calculate the points only requires a few trigonometry operations.

A disadvantage to this design will be the increased complexity from the toroid shape as there will be less internal space to contain all of the components.

Another downside of this design will be the relative slow speed as the motors have to move a relatively high amount of mass.

Option 2: Using a Mirror Galvanometer to Direct the Beam

The second option considered using two perpendicular rotating mirrors which are able to direct the LiDAR measurement beam. Mirror galvanometers are currently used in systems with laser scanning systems. [ref 1]



Closed loop mirror galvanometers are also used in laser TVs, so the accuracy should be easy to attain, and the body should fit easily on a standard surveyor's tripod.

Another advantage of this option is the increase of rotational acceleration due to the decreased in mass and therefore reduced rotational inertia.

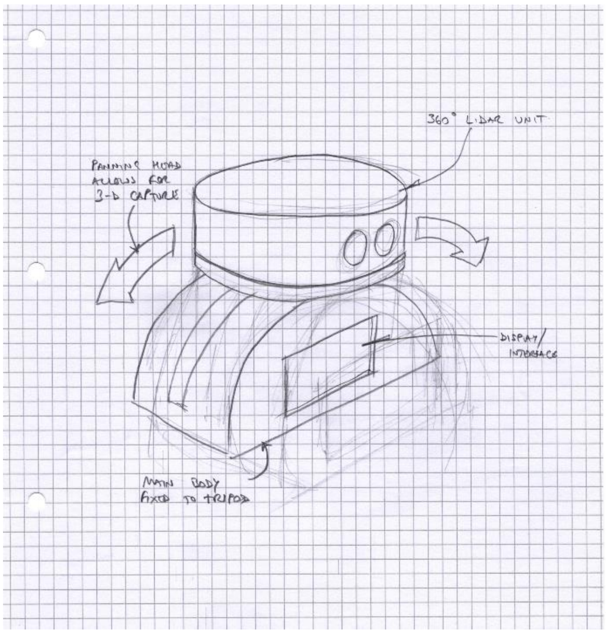
The disadvantages include the fact that the mirrors are sensitive to dirt and potential external interference.

The equipment required would likely exceed the financial budget of the project, and the learning curve would be steep.

Additional optical equipment will be required to be able to aim directly downward, add multiple beams, for LASER pointer and LiDAR sensor adds complexity.

Option 3: Oscillating 360° LiDAR Scanner

The final option is to utilise a fast-spinning 2D LiDAR sensor typically found on items like robotic vacuum cleaners and self-driving cars. and rotate it perpendicularly over a 180° range to obtain a full three-dimensional scan.



This option offers the fastest scan speeds of the three designs as the head spins multiple times a second, taking thousands of measurements every rotation. [ref 2]

Adapting the scanner to operate in 3D will be difficult, as rotating a spinning mass will cause unknown gyroscopic forces; any imbalances could cause unwanted vibration.

Being able to stitch scans together would require a SLAM (Simultaneous Localisation & Mapping) algorithm and would become complicated; the required computing power may become too demanding.

The design would also struggle to fit on an existing surveyor's tripod as the sensors are designed for vacuum cleaners or other autonomous bots.

Analysis & Conclusion

One of the main problems with existing single-scene scans is the creation of 'shadows', whereby nearby objects obscure (or shadow) objects in the background. Therefore, there is a requirement to stitch multiple scans together. Option 3 would greatly struggle to reference itself in discrete scans.

Option 2 requires a great deal of specialist optical equipment at a significant cost. In addition to this, the mirrors would be too fragile for construction situations. Option 2 is best suited to laboratory settings.

Option 1 seems to offer the greatest chance of success, prior experience can be built on, so the learning curve is shallower, however, this option would also be the slowest to scan.

A Pugh Decision matrix was produced to assess all three design options against the original product dimensions. Advantages were given a +5 score and coloured green; disadvantages were given a -5 score and coloured red. Neutral scores remained at zero.

The results from the decision matrix matched the original analysis with the total scores being:

Design 1 – Standard Design	25 points
Design 2 – Mirror Galvanometer	10 points
Design 3 – Pitching 360-degree Scanner	5 points

The breakdown of these scores can be seen in the next section.

Pugh Decision Matrix

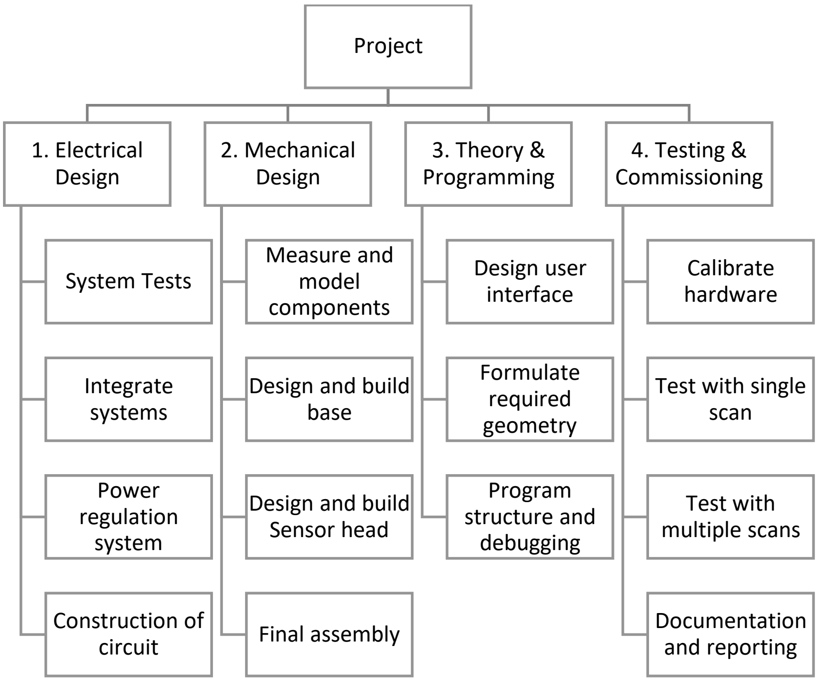
Criteria	Design 1 – Standard Design	Design 2 – Mirror Galvanometer	Design 3 – Pitching 360° Scanner
Functionality	Default design for surveying equipment: +5	Used in high precision applications: +5	Used extensively for fast 2D mapping applications: +5
Environmental Operational Conditions	Closed body design offers protection: +5	Negatively impacted by dust -5	The panning motion may become impaired by dust: 0
Size & Weight	Heaviest & largest due to motors: 0	Lighter due to smaller motors: +5	Smallest due to low profile scanner: +5
Aesthetics	N/A – function before form		
Ergonomics	Size allows for easy operation and interface: +5	Similar easy operation and interface: +5	Operation to find fixed points is complicated: -5
Reliability	Closed loop motion system gives high reliability: +5	Mirrors are prone to knocking which causes inaccuracies: 0	Fast moving parts could cause early failure points: 0
Maintainability	N/A – No user-serviceable parts.		
Manufacturability	N/A – This is a one-off item.		
Compatibility	N/A – there are no existing systems to match with		
Efficiency (Power)	Heavy & large nature makes this the least efficient: 0	The smaller motors will consume less power: +5	Faster scans in theory require less overall power: +5
Cost	Constructed from off-the-shelf items: +5	Mirror galvanometers add expense: -5	Rotating LiDAR scanner adds expense: -5
Ethics (Compliancy & Legal)	N/A – all designs must comply with the same legislation		
Disposal	N/A – all designs must comply with the same disposal regulations		
Sustainability (Pearson Set Theme)	All solutions are aiming for the same sustainability outcome in ensuring accurate surveys to reduce on-site waste.		

Plan and Program of Works

Work Breakdown Structure

To aid in the planning of the project, a work breakdown structure was created to isolate the various sections and individual high-level tasks within.

As this is a research task, there are bound to be unknown tasks which cannot be foreseen at the early stages of the project, however, the above umbrella terms should catch all tasks required.



Program of Works

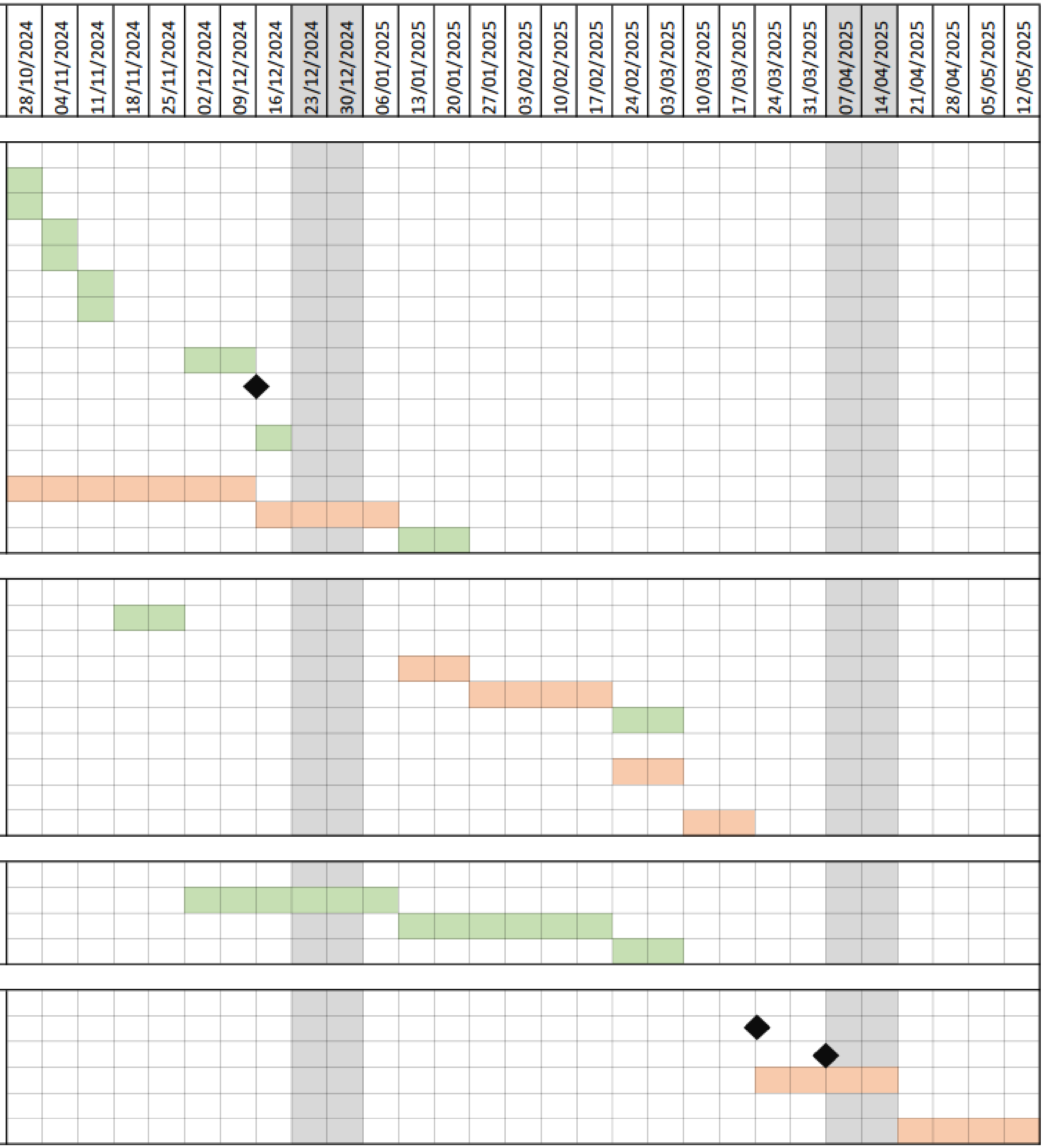
From the work breakdown structure, it is possible to formulate a program of works. The method used is as a graphical Gantt chart with coloured bars to show the critical path.

In a similar way to the work breakdown structure, it is not possible to determine the exact time periods for each process, however, to try and tie in with the academic calendar and the due date for assignments, the two following critical dates were set:

Start Date:	Monday 28th October 2024
End date:	Sunday 18th May 2025
Project Period:	32 weeks

A program of works is included below.

Ref	Description	Duration	Dependancies
1	**Electrical**		
1.1	Systems tests		
1.1.1	LiDAR sensor	1 week	
1.1.2	Laser pointer	1 week	
1.1.3	Drivers & motors	1 week	
1.1.4	Angle sensors	1 week	
1.1.5	SD Card	1 week	
1.1.6	Touch display interface	1 week	
1.2	Full integration		
1.2.1	Build test rig	2 weeks	Item 2.1
1.2.2	Single dimension test	milestone	
1.3	Power circuitry		
1.3.1	Battery & charging circuit	1 week	Delivery time
1.4	Circuitry		
1.4.1	Breadboard tests	7 weeks	
1.4.2	Prototype final	4 weeks	
1.4.3	Build final	2 weeks	
2	**Mechanical**		
2.1	Preliminary works		
2.1.1	Temporary test mount	2 weeks	Item 1.2
2.2	Base		
2.2.1	Tripod mount	2 weeks	
2.2.2	Rotating body	4 weeks	item 1.4.2
2.2.3	Display mount	2 weeks	item 2.2.2
2.3	Sensor head		
2.3.1	Sensor mount	2 weeks	item 2.2.2
2.4	Final Construction		
2.4.1	Complete final assembly	2 weeks	
3	**Programmatical**		
3.1	Thoery		
3.1.1	Maths	6 weeks	
3.1.2	Process & Program	6 weeks	item 1.4.2
3.1.3	User interface	2 weeks	item 3.1.2
4	**Testing & Commisioning**		
4.1	Testing		
4.1.1	Test - full scan	milestone	item 2.4.1
4.1.2	Test - multiple scan	milestone	item 4.1.1
4.1.3	Debugging and calibration	2x2 weeks	item 4.1.1 & 4.1.2
4.2	Commisioning		
4.2.1	Documentation	4 weeks	item 4.1.3



Electrical Design & Construction Process

Preface

In 2021, a study was conducted at home to find out if it was possible to construct a three-dimensional scanner using hobby-grade components such as a 28BYJ-48 stepper motor for azimuth control, a MG996R servo motor for altitude control and an HC-SR04 ultrasonic sensor.

After this, the distance sensor was upgraded to a Benewake TF-Luna LiDAR module the motors upgraded to NEMA17 shape stepper motors with A4988 drivers. The works carried out during this initial phase has formed the basis of the project foundations and design.

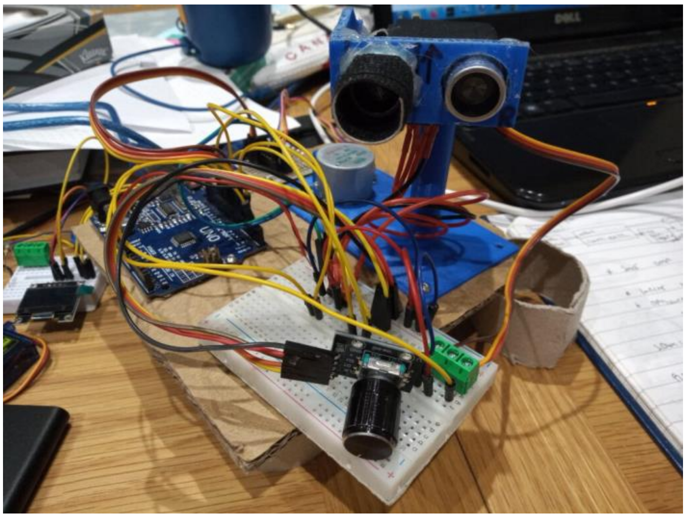


Figure 1: Initial Concept from 2021

This project set out to build upon the lessons learned previously as well as implement a number of new features such as absolute angle positioning (rather than relative position), a proper user interface, and better sensors.

Overall Systems Design

An outline systems design was sketched in the log book to lay out all of the relevant subsystems and how they inter-connected with each other.

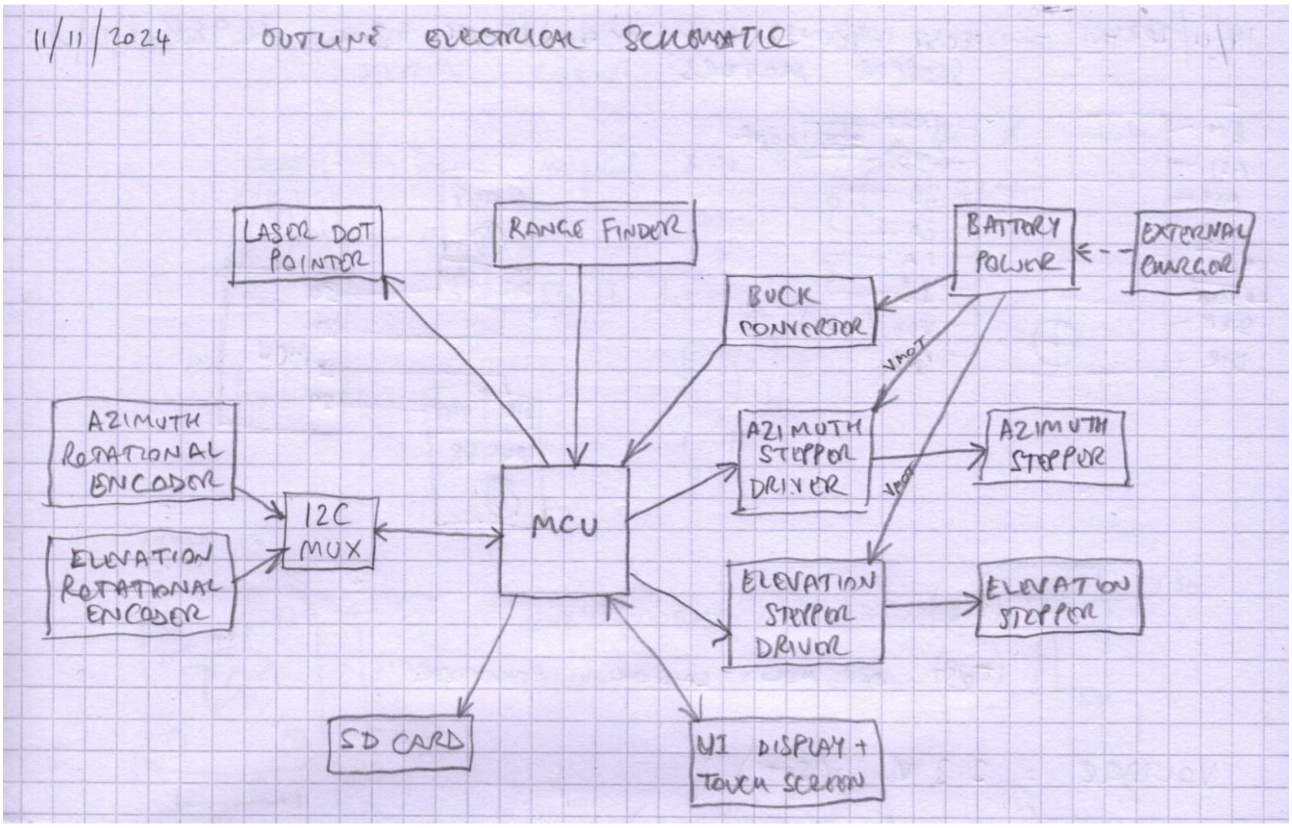


Figure 2: Outline System Design

Microcontroller

The microcontroller is the brains of the operation and has many roles such as reading sensors, carrying out the calculations, and controlling the motors. Previous tests used an 8-bit AVR microcontroller (Arduino), however, the small data bus limited the data types to floating point numbers, rather than being able to utilise the greater accuracy that comes with double-floating point arithmetic [ref 5].

The microcontroller selected was the Teensy 4.1 which features a 600Mhz CPU for faster calculations, 8MB of flash storage memory, onboard SD card reader and a 64-bit floating-point math unit. A comparison table below shows how the specifications differ from the initial Arduino.

Feature	**Arduino**	**Teensy 4.1**
CPU	ATMega328P running at 16Mhz	ARM Cortex-M7 running at 600Mhz (x37.5 times faster)
Flash (program) memory	32 kB	8 MB (x250 times larger)
RAM	2 kB SRAM	1024 kB (x512 times larger)
Bus width	8-bit	32/64-bit
In-built SD card	No	Yes
Digital I/O pins	14	55

[ref 6] and [ref 7]

Motors & Drivers

NEMA17 style motors were selected for this project. The motors are found in many other places such as 3D printers and offer a 200-step resolution with many online resources to help interface them.

The torque of the motor is dependent on the variant and directly correlates to the depth of the motor body. Smaller 'pancake' style motors produce 13N.cm, whereas specific high-torque variants can produce 65N.cm. [ref 8]

Unfortunately, the microcontroller is unable to directly drive these motors so a specific driver has to be used. The drivers selected for this project were a pair of A4988 drivers. These are able to deliver up to 2A of current to the motors.

As 200 steps per revolution equates to 1.8^o per revolution, which is far less than the required 0.29^o resolution required, the motor drivers will be used in $1/16^{th}$ micro-stepping mode. By varying the current between the adjacent coils inside the motor, it is possible to increase the rotational control of the motor shaft.

Therefore, 200 steps divided by 16 gives a total number of 3200 steps per revolution, thus bringing the angular resolution down to 0.1125^o which meets the necessary specification.

The motors used had a double ended shaft to allow one side to drive the necessary components, while also having a shaft at the rear to house the di-pole magnet for the rotary encoder.

Rotary Encoders & Multiplexer

While it's important to have a motor that can move in small increments; there also needs to also be a way of measuring the angle in equally small increments. A pair of AS5600 magnetic rotary encoders were selected for the project as they boast a 12-bit angular resolution.

Having 12-bit resolution means that there are a possible 2^{12} different values, ranging from 0 to 4096 (binary 0000 0000 0000 to 1111 1111 1111). The 4096 divisions within a rotation gives a resolution of 0.088°, which still meets the necessary client specification.

These sensors communicate over the I2C protocol, and unfortunately have a fixed I2C address (0x36), therefore a multiplexer is required to interface more than one sensor at a time.

The multiplexer chosen for this design is the PCA9548 8-channel I2C multiplexer. This particular device is able to handle 8 different I2C devices with bi-directional communication up to 400Khz. The multiplexer also handles the signal from the LiDAR sensor, too.

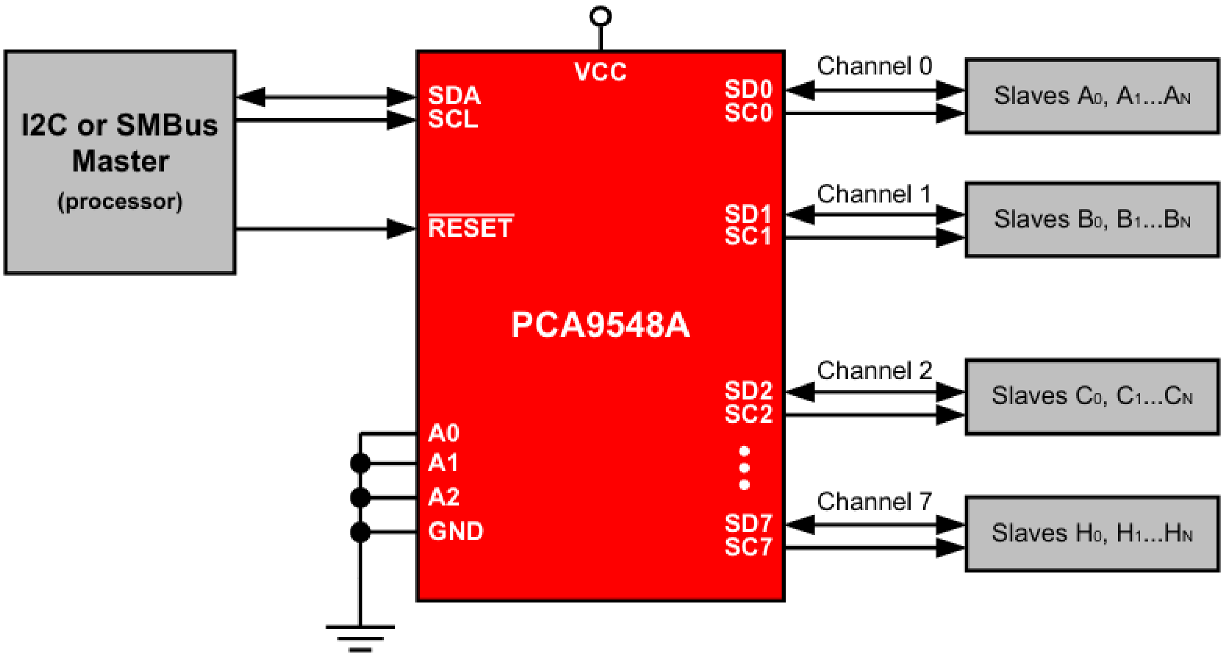


Figure 3: Simplified multiplexer schematic [ref 9]

The design used the following channels for the various I2C devices.

Channel 0 = (Not used)
Channel 1 = LiDAR Sensor
Channel 2 = Azimuth AS5600 rotary encoder
Channel 3 = Altitude AS5600 rotary encoder
Channel 4 = (Not used)
Channel 5 = (Not used)
Channel 6 = (Not used)
Channel 7 = (Not used)

Display & Touch Screen Interface

The touch screen display used for this project is the 3.2inch ILI9341 display with resistive touch interface. Both the display and touch sensor work over the SPI bus, which simplifies the wiring to the microcontroller.

A carrier board was designed and built to combine the clock and data signals for the SPI bus, as well as other necessary shared power and ground connections. Below are extracts of the design and construction of the carrier board.

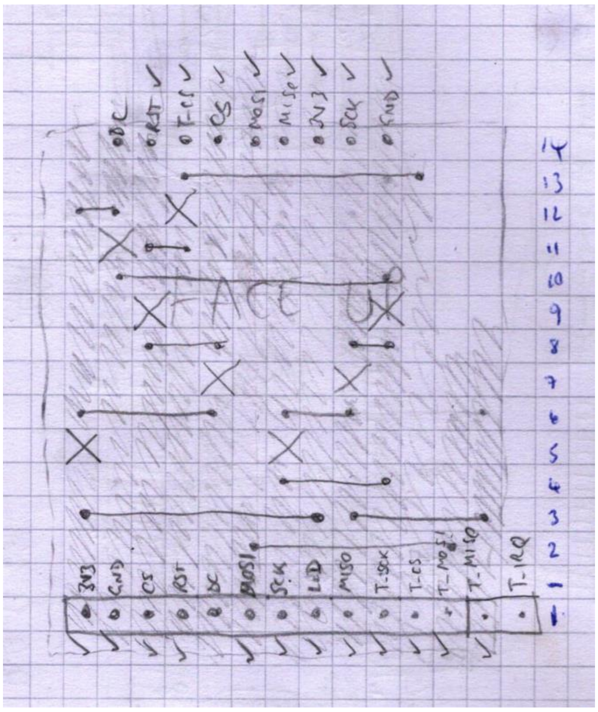


Figure 4: Design of carrier board

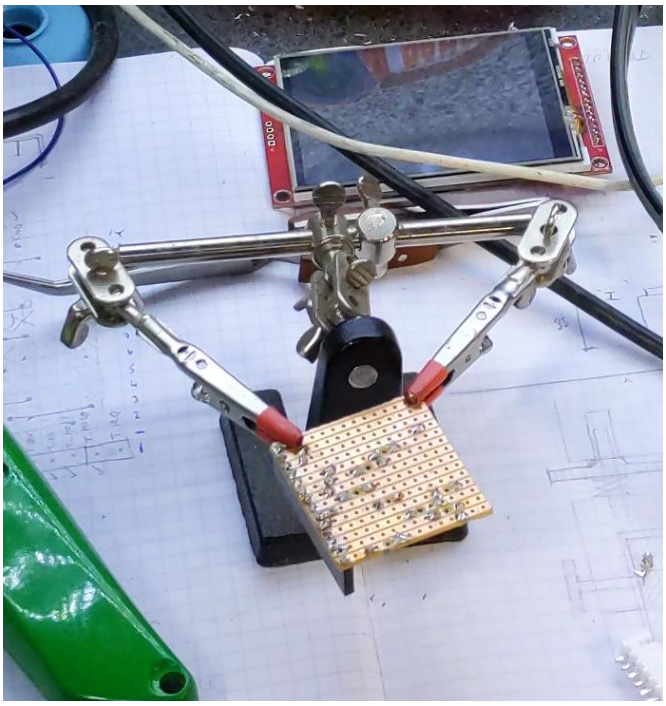


Figure 5: Construction of carrier board

LiDAR Distance Sensor

The previously used LiDAR sensor had a maximum range of 8.0m [ref 10], which is below the necessary client specification, therefore a new sensor had to be selected.

The other key feature to consider in the sensor selection is the beam divergence. A wide beam will not return accurate results when looking at the transition area between two surfaces with different distances, as demonstrated with the graphic.

A sensor with a wide beam divergence will produce results that have rounded corners as the sensor interpolates the data between the two readings.

As such, the chosen sensor was the Garmin LiDAR Lite V3HP because it offered a 40m range, beam divergence of 8milliRad (approx. 0.5°), and a 1kHz update rate.

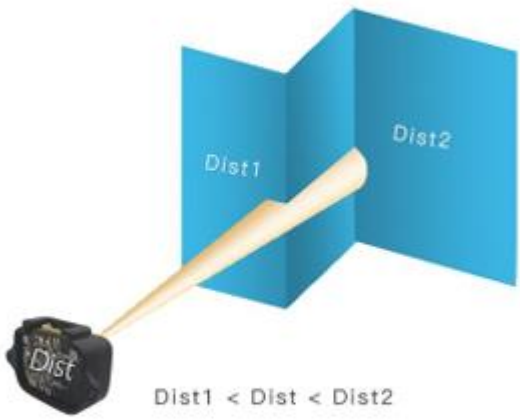


Figure 6: Beam divergence across dissimilar distances

In addition to this, the sensor is rated to IPX7 for the protection against water ingress. [ref 11]

LASER Pointer

In order to be able to know where the LiDAR sensor is measuring, it is necessary to have a laser dot to be able to locate the direction. Laser selection was balanced between having a visible dot at the required distance whilst also still being safe, especially as this device is able to move in a full 360o angle.

The final selection was a 5mW red laser diode with a 650nm wavelength (red). This is a Class 3R product which means that it could potentially cause eye injuries with direct viewing, however, the HSE deems them as a low risk due to the natural aversion behaviour of the eye to blink if exposed to bright lights. [ref 12]

Laser safety signage is necessary for the laser pointer, stating the specific laser class in use. The laser used for the LiDAR module is classified as a Class 1 laser device under EN/IEC 60825-1 2014. This class of laser is the only class deemed "eye-safe".

Figure 7: Laser safety signage

Tests were carried out to determine the current being drawn by the laser diode, and at 3.3V, the current draw was 13.4mA. As the microcontroller has a max output current of 4mA, a driver circuit was required.

The driver circuit was designed and constructed with a 2N3904 NPN BJT, with a 1kΩ base resistor, as shown below.

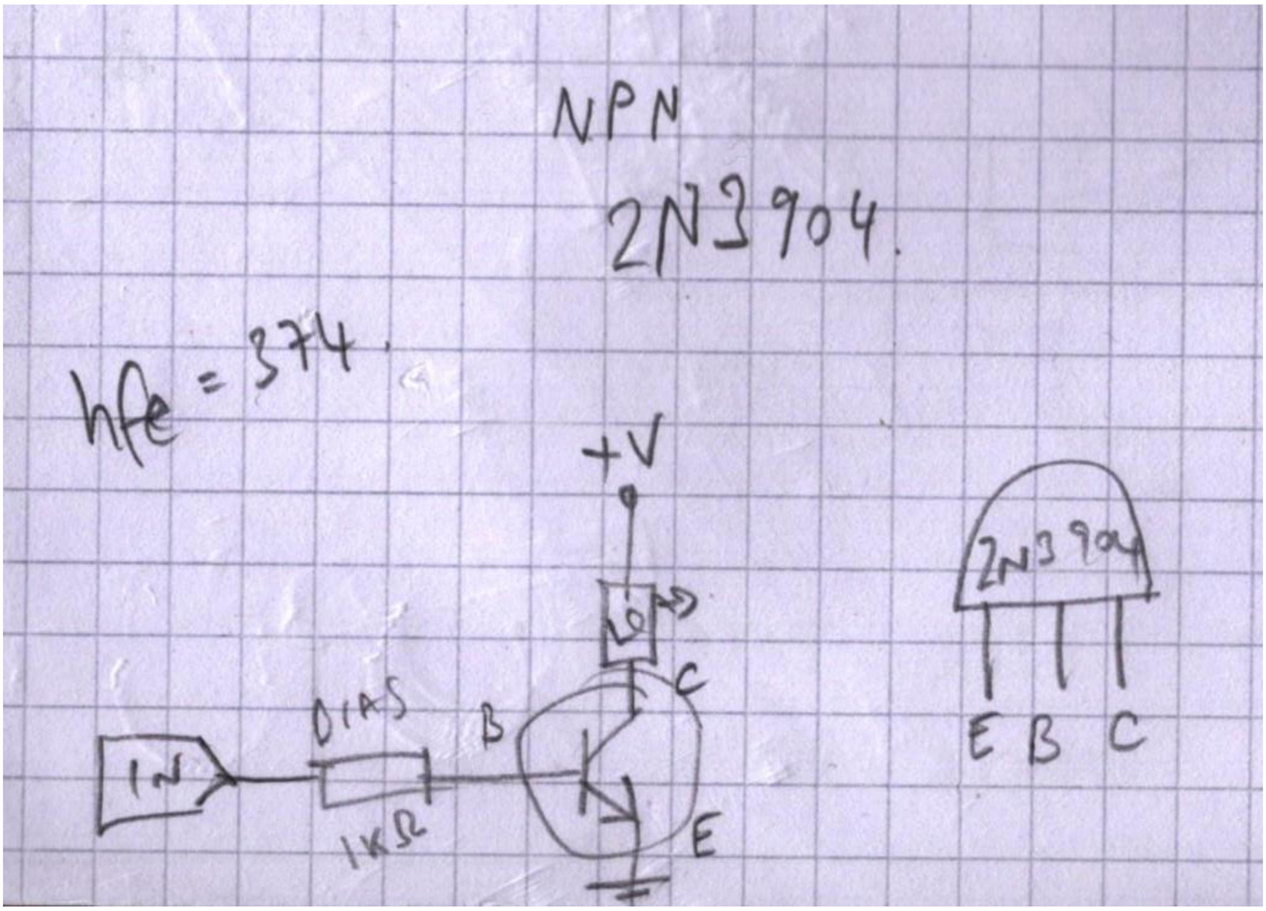


Figure 8: Design of laser driver circuit

Power, Regulation & Charging

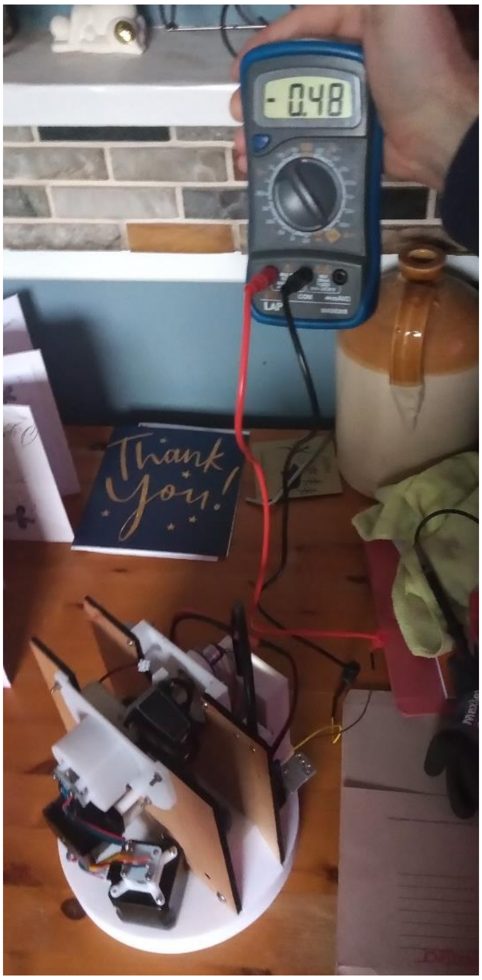


Figure 9: Current measurement reading

The company had stipulated that the project is portable, therefore it was necessary to size a suitable battery supply for the scanner.

For greater power density, a lithium-chemistry powered battery was chosen because comparable lead acid cells would be significantly heavier, and other technologies like NiCd wouldn't power the scanner for as long.

The two main properties of any portable power source are the battery voltage and the battery capacity. In regards to voltage, the battery needs to be able to support the motor movement which required a minimum of 8V, ideally >9V. Therefore, a 3S LiPo gives a nominal voltage of 11.1V and a voltage range of 9.0-12.6V.

The initial battery pack had a capacity of 6000mAh. However, after subsequent testing found that the current draw of the scanner with both motors running was measured at 0.48A, the battery was downsized to a pair of 2200mAh packs.

Lithium based technologies do pose a fire risk if treated improperly or damaged. Therefore, a dedicated balanced LiPo charger was purchased to reduce the risk of overcharging.

All of the internal electronics run off 3.3V, so it was necessary to regulate the battery power to a standard 3.3V. The microcontroller does accept 5V and has an onboard 3.3V regulator capable of 250mA, however, to prevent the risk of the onboard regulator from burning up, an external regulator was used.

Initially an LM1117 3.3V regulator was chosen as it had an 800mA capacity and featured a low drop-out design. Unfortunately, the regulator got very hot, very quickly and would shut down after 30 seconds as it was burning about 4.3W.

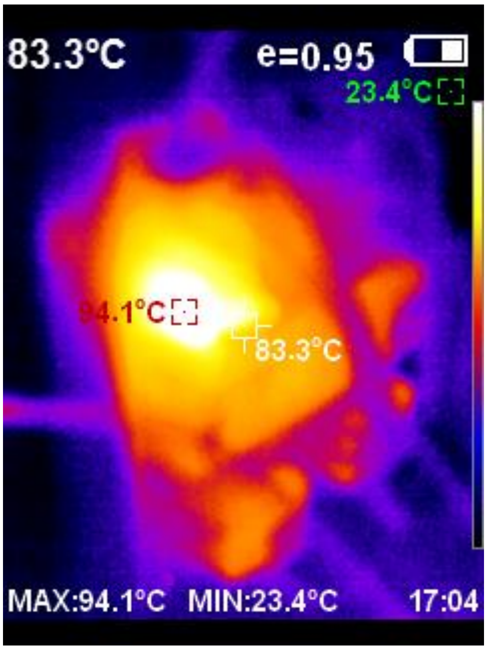


Figure 10: Thermal camera image showing temperature of voltage regulator

A heatsink was fashioned from a block of aluminium, and screwed to the back of the regulator with some thermal paste used at the junction.

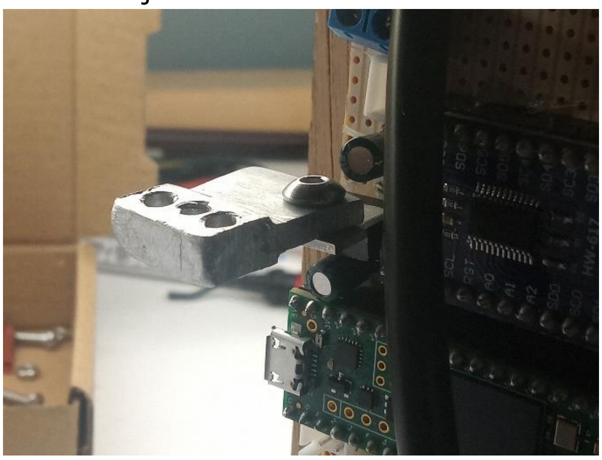
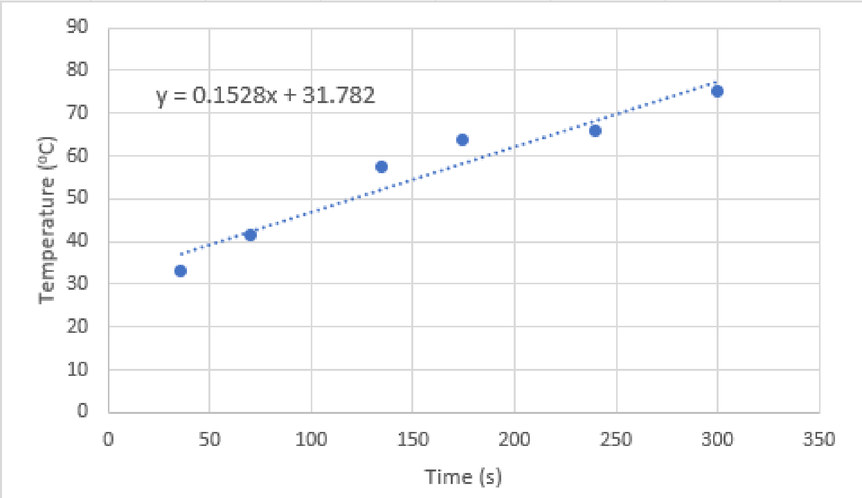


Figure 11: Aluminium heatsink on regulator

The thermal characteristics of the heatsink were measured over time and plotted on the graph to the right. The experiment was ended after 5mins (300 seconds).



Because the results from the test showed now signs of the temperature plateauing, a small fan was purchased to use as active cooling (but was never tested).

Due to the inefficient nature of the LM1117 voltage regulator, the decision was made to change it for a more efficient DC-DC buck converter. This converter needed to be affixed to a small carrier board to convert the 4 pins to a 3-pin drop-in replacement, pictured below with the thermal camera image.

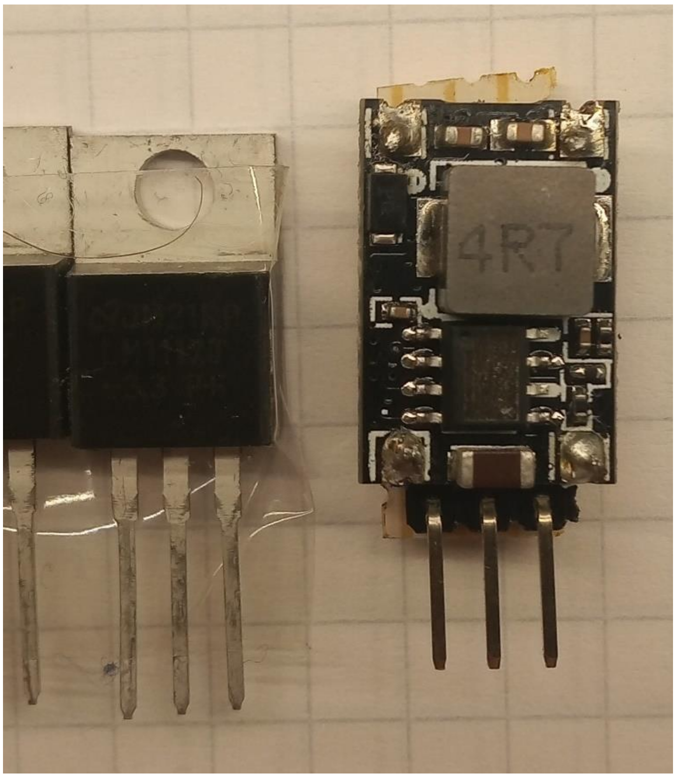


Figure 12: LM1117 regulator (left). DC-DC buck converter (right).

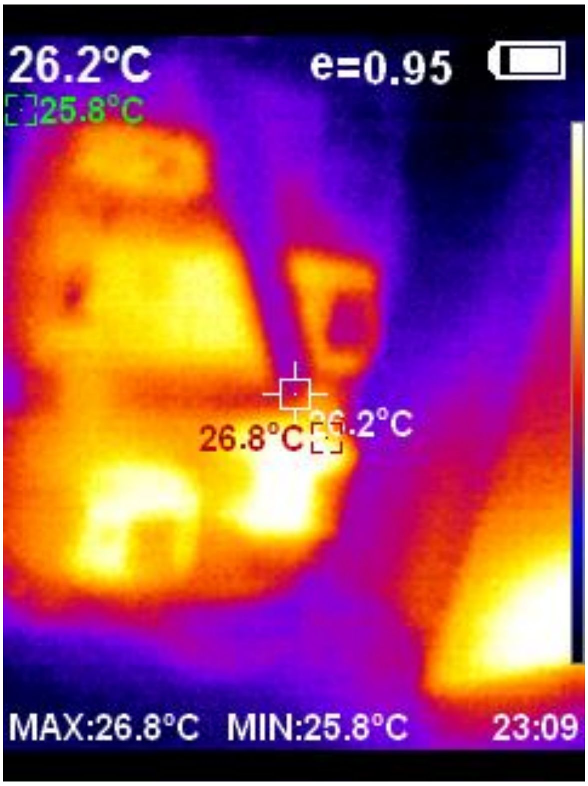


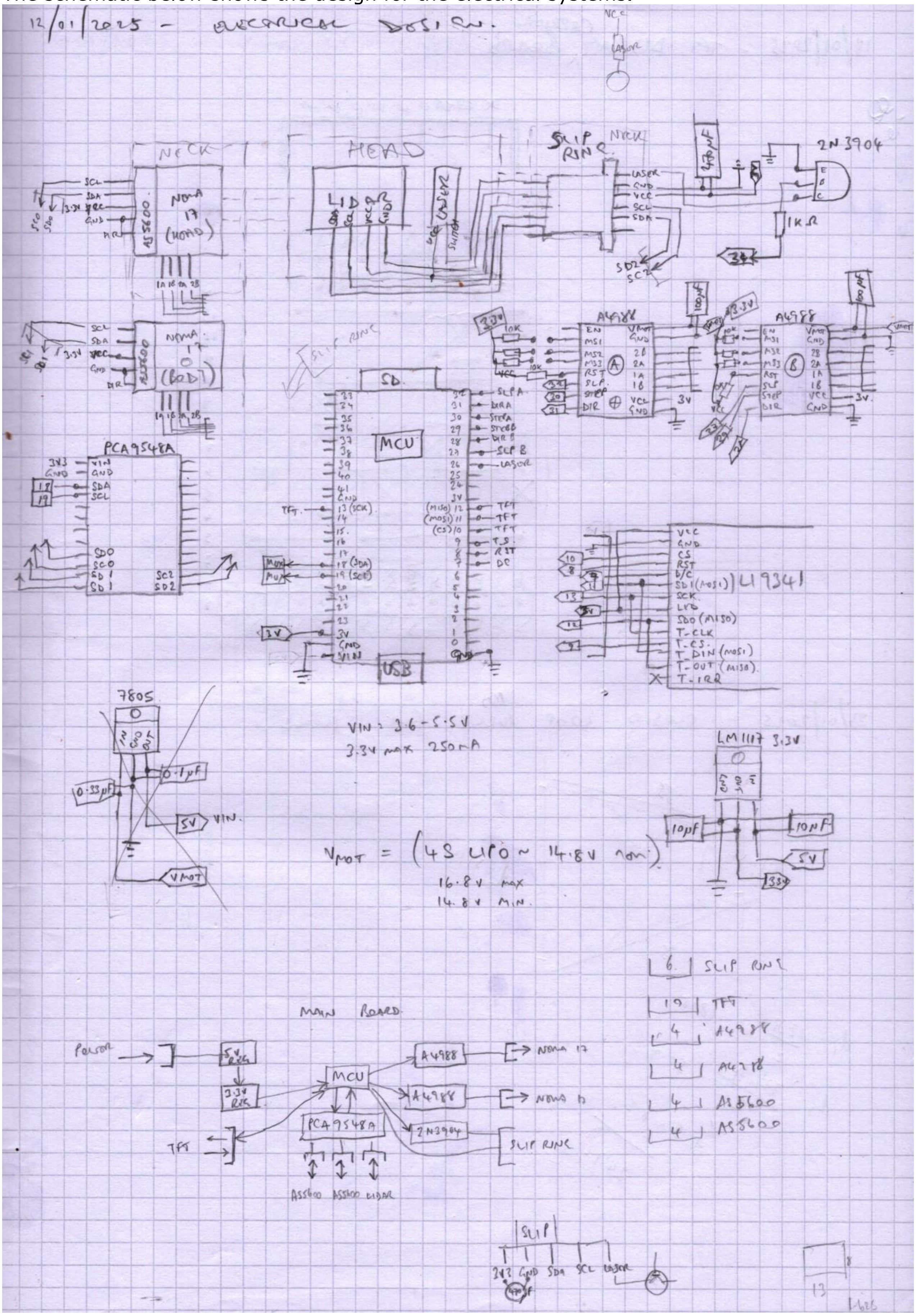
Figure 13: Thermal image with the DC-DC converter, showing max temp as 26.8ºC

To isolate the power from the device, a SPST toggle switch is used in-line with the positive lead of the battery which is rated to 6A at 125V AC. The DC rating of this switch is unknown.

A voltage divider circuit is used with an analogue input pin of the microcontroller to measure the battery voltage. This was calibrated with a variable DC power supply over a range of voltages.

Overall Electrical System Design

The schematic below shows the design for the electrical systems.



System Test

The circuit was constructed using solderless breadboards and jumper cables and attached to a custom designed 3D printed test jig. A simple interface was programmed into the touch display to allow the accuracy to be tested as documented below.

The test plan involved measuring the distance across the head of a door frame across from the room. The door frame had an approximate measurement of 800mm, and the distance of the door frame from the test rig was approximately 4.0m.

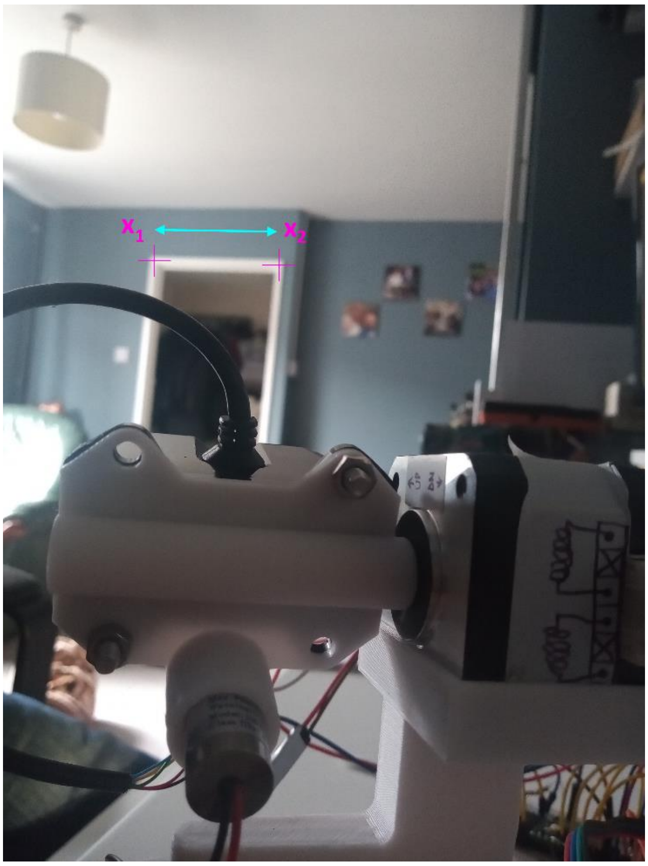


Figure 15: Test rig line of sight at door frame

Figure 14: Measurement of door frame

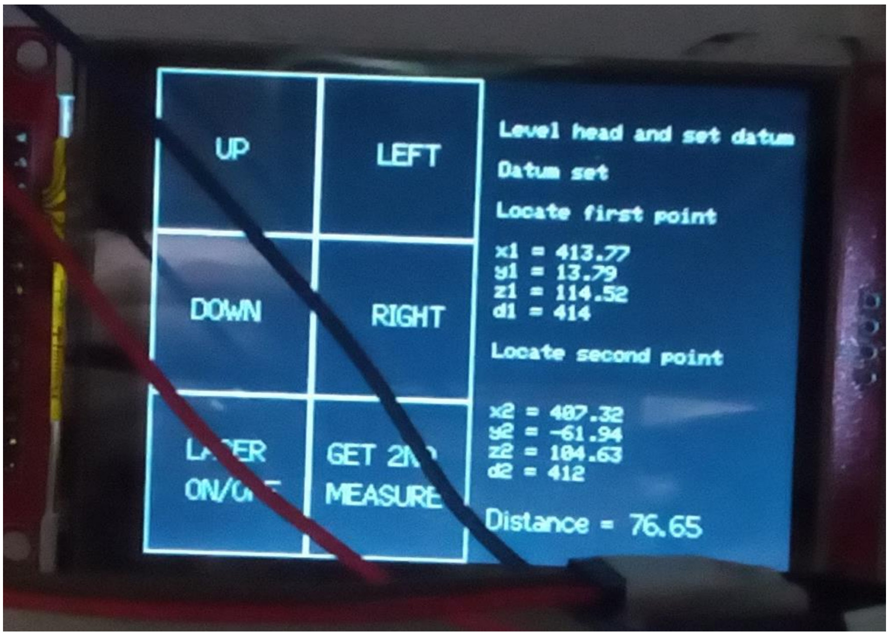


Figure 16: Display showing the results of a test

The result of 76.65cm can be seen on the display shown in Figure 16.

This is calculated by working out the three-dimensional hypotenuse between two points.

As the target measurement was 80cm, this test had a measurement of 76.65cm, therefore with an error of 3.35cm (4.2%).

Given the amount of 'blutac' that was used, this was considered a great success!

Final Construction

The final circuit board was constructed using Veroboard/stripboard, JST 2.54mm connectors, female pin headers, wire and other passive through-hole components, as shown in the design below.

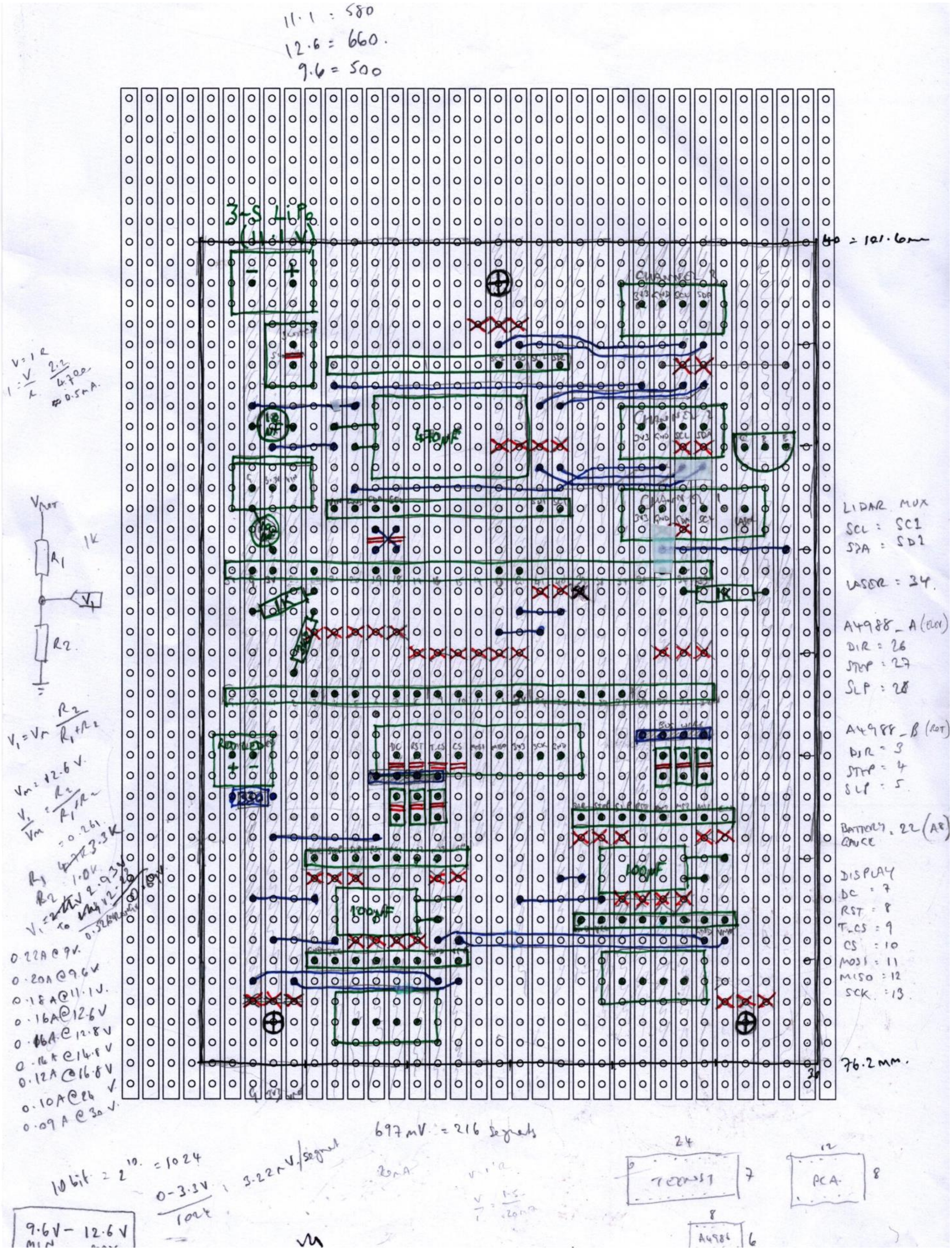


Figure 17: Circuit diagram using custom tempate

Two photographs showing the face and reverse of the circuit board. Note that the reverse image is mirrored.

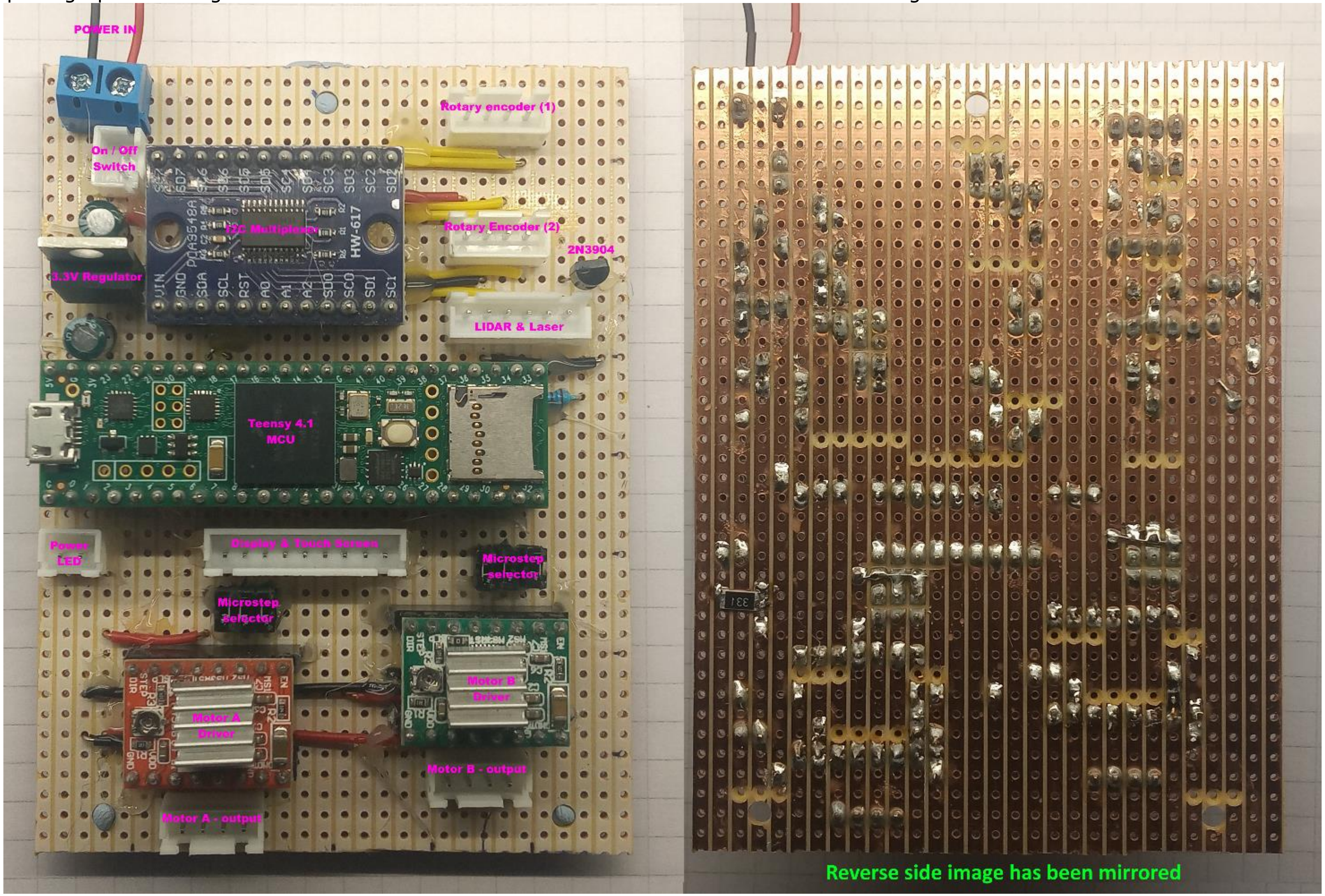


Figure 18: Final circuit construction

Mechanical Design & Construction Process

Preface

As this project was to be built at home, therefore access to equipment, tools and machinery were limited. The only equipment available for building the project was:

- An FDM 3D printer with a build volume of 200x200x200mm
- An SLA 3D printer with a build volume of 130x78x160mm
- A 10W laser cutter, with a platform size of 370x370mm and max 6mm cut depth
- Basic power tools such as a drill press, jigsaw, and angle grinder
- Basic hand tools including a tap & die set.

All computer aided design was carried out on ProgeCAD 2018 to produce the three-dimensional models. These were then 'sliced' using suitable software for the machine.

Tripod Mount & Levelling Base

The first item to measured and modelled was the existing tripod, as this would be the basis of build. Initially a rubbing was taken and analysed for the dimensions.

From these measurements, a model was designed in CAD and subsequently printed in PLA to test that they were correct.

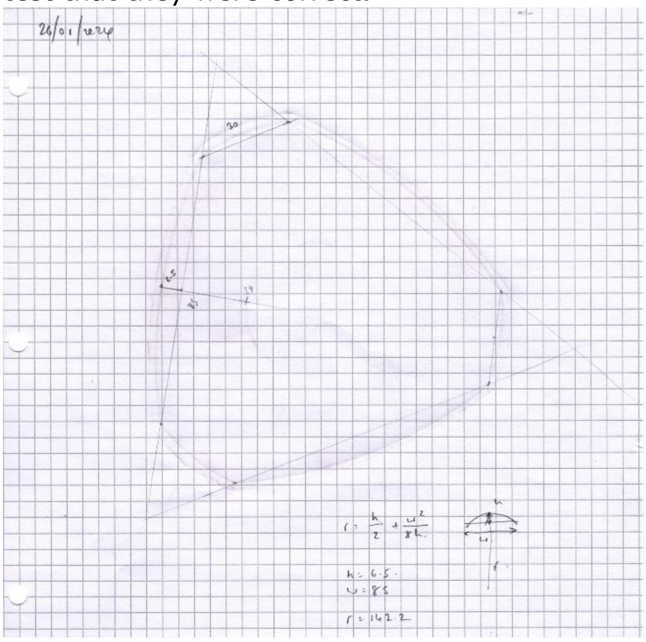


Figure 20: Rubbing taken of existing tripod

Figure 19: Test 3D print to check the dimensions

Typically tripods have a central mounting screw that sits through the hole in the middle; this screw would nullify the ability to take measurement through the centre to the floor. As such, a different method of mounting the scanner to the tripod was designed.

The mounting screws were designed to affix into the underside of the scanner in three locations at 120o intervals. Connected to the mounting screws was a clamping foot and tightening knob.

Inspiration for the levelling base was taken from the technology used for manual bed levelling of 3D printers; using spring-loaded points between two plates of 6mm aluminium, allowing for full level control.

The initial design was sketched up in the log book before being committed to CAD. As there was no access to a suitable CNC machine, the design was printed on to paper and transferred to the aluminium plate, before being cut with a jigsaw and hacksaw.

The holes were drilled using the drill press, and where necessary, countersunk and/or tapped to receive a screw thread. The internal hole was formed using a bi-metal hole saw.

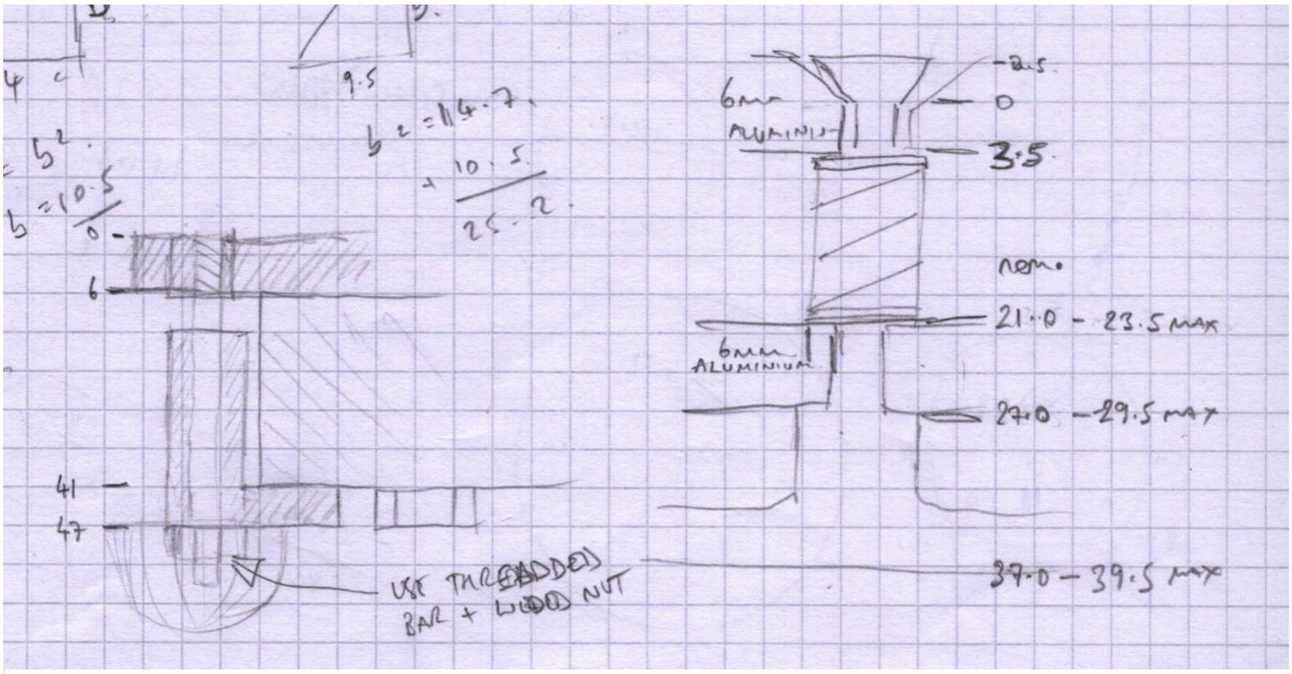


Figure 21: Sketch design of the base plates

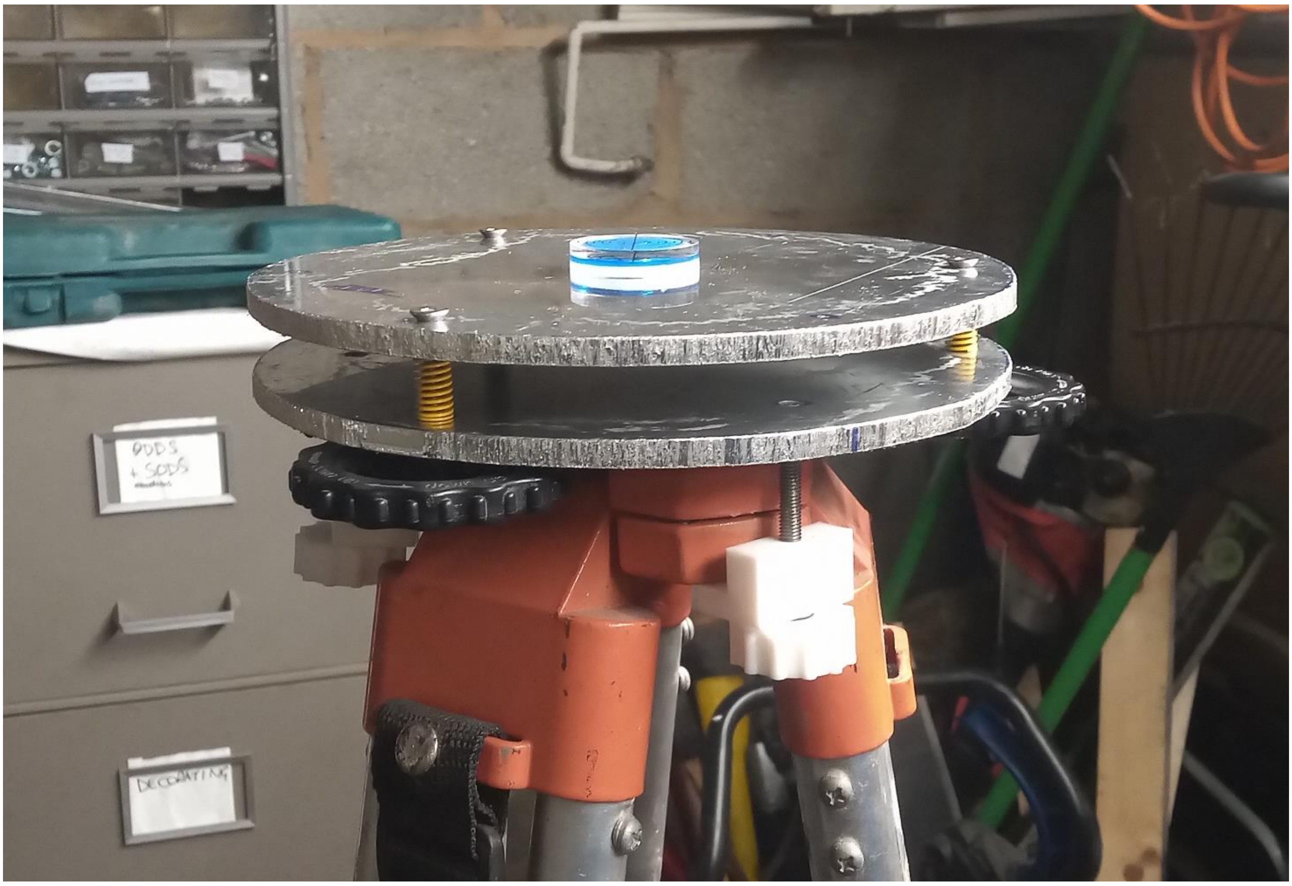


Figure 22: Construction of baseplates

Rotating Base

For the azimuth rotation, a "lazy Susan" type design was opted for, with 10mm ball bearings used to reduce friction with a custom bearing cage printed to hold them in place.

The differential motion of the upper stage was driven from a dual-shaft stepper motor fitted with a 20T pully and meshed with a ring gear formed with GT2 timing belt. The magnetic rotary encoder was fitted to the top of the other shaft. The final gear ratio of the base ring gear to motor was 210:20 (or simplified to 10.7:1)

To prevent the two halves of the base from coming across, two additional geared idler pullies were fitted. All of the pullies had a flange that wrapped around the ring gear, thus holding the two parts together.

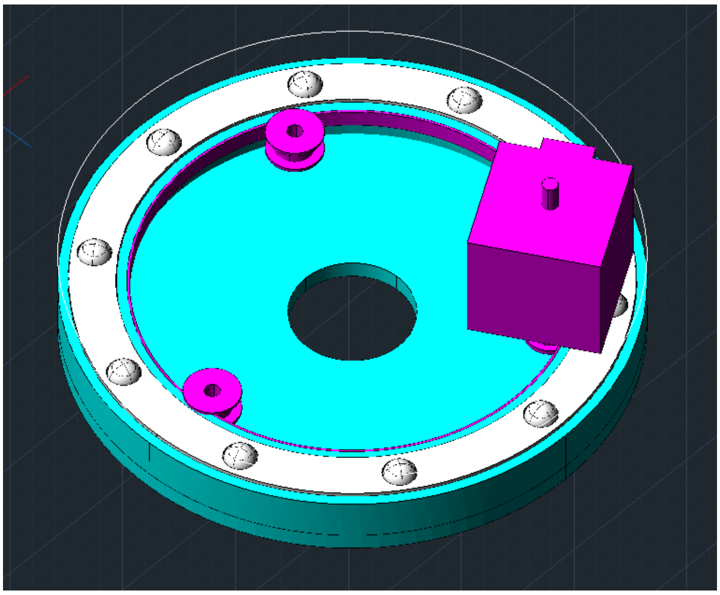


Figure 23: 3D model design of rotating base

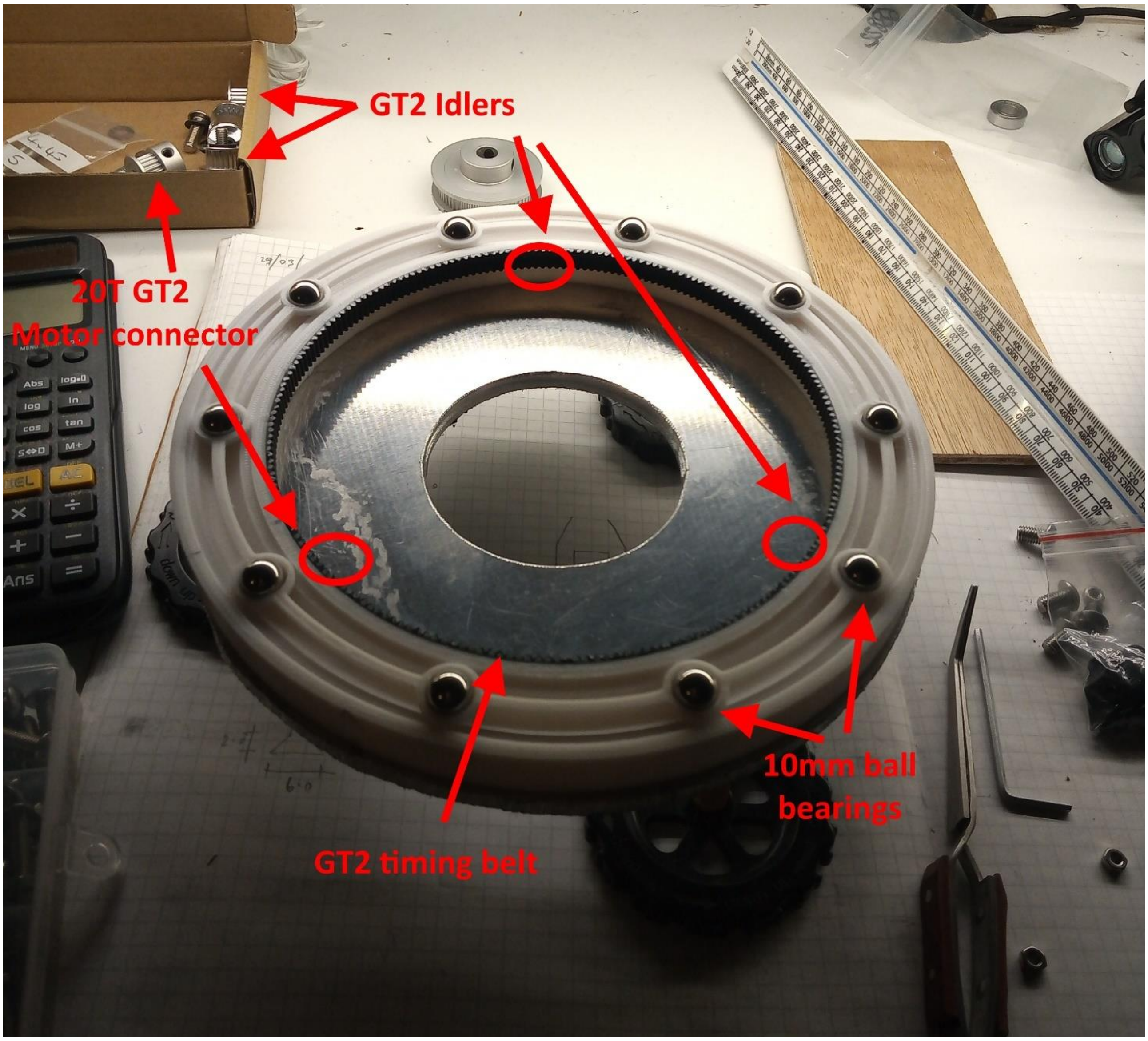


Figure 24: Part construction of rotating base

During the construction of the base, it was discovered that the 3D CAD software generated circular bodies as 24-sided polygons. For smaller diameter items, this doesn't matter, however, at the radiuses used, this created unwanted facets which lead to greater friction.

Thankfully this was solved by changing the FACETRES from 0.50 to 10.0, meaning that any circles were rendered as 96-sided polygons – four times smoother than previous.

No grease or other lubrication was used because of the unknown effect against the PLA plastic used throughout the project.

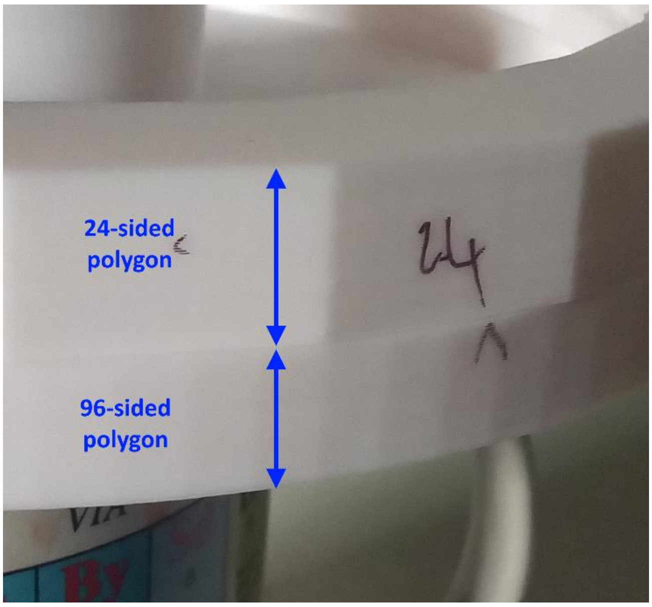


Figure 25: Difference between 24-sided and 96-sided polygons

Main Body

The main body was designed so that the motors and rotational encoders would be on one side, and the electronics and battery would be on the other side; aside from the azimuth motor, all other items would be affixed to the main body.

The body constructed with two sheets of laser-cut plywood to form the mounting points for the items. These sheets of ply were fixed to a central block, which itself was fixed to the rotating base.

During this time, it was found that the laser cutter required calibration as the shapes it was forming were note dimensionally accurate. To remedy this issue, all of the belts, pullies and wheels on the laser cutter were serviced along with the laser lens.

The central block features a cable run to allow for the motor control and sensor wires to run back to the main circuit board. The central block also housed the bubble level (which can be seen in yellow in Figure 26).

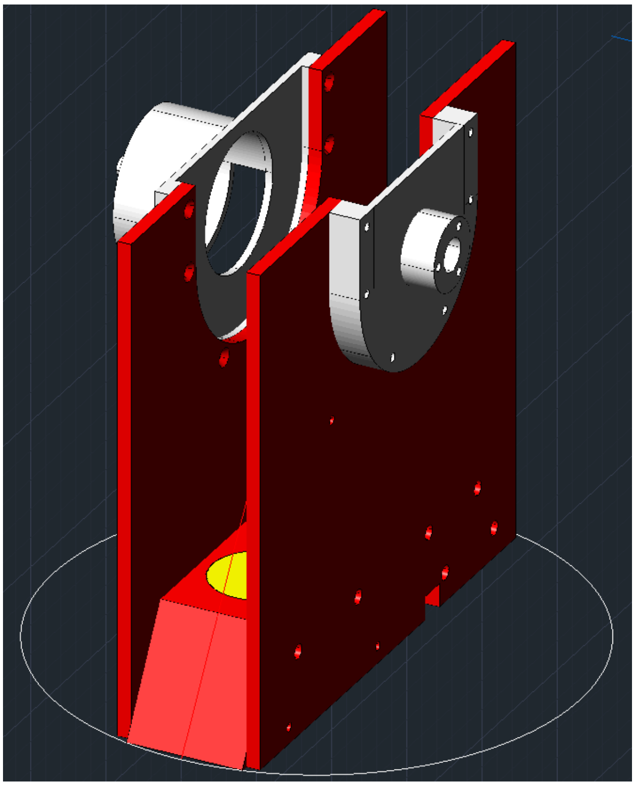


Figure 26: 3D model design of main body

Two side panels (shown in white in Figure 26) were designed and 3D printed in PLA plastic. The left-most side panel in the foreground housed the bearing for the head as well as forming a mounting point for the slip ring, and giving clearance for the cable coming from the LiDAR sensor. The side panel to the right housed a bearing for the head, as well as the altitude pully and mounting points for the rotational sensor, while also giving clearance for the laser diode.

Sensor Head

The sensor head contains the LiDAR distance sensor as well as the laser diode dot and the slip-ring to allow the head to spin without the cables strangulating the movement.

An initial arrangement was thrown together using 'blutac'. During this phase, it was noted that as the LiDAR lenses must be central, the width between the sensor lenses and the laser diode lens was greater than the diameter of the hole through the tripod.

As such, the laser diode was moved behind the LiDAR sensor so that it could be tucked in closer to the centre.

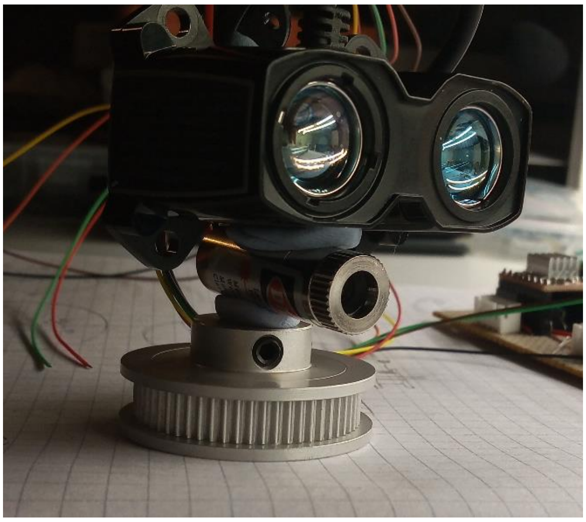


Figure 27: Initial concept for sensor head

The head also had to contain the dipole magnet for the rotary encoder, as well as a shaft for the pully and cable ways for the various data and power wires. The head was iteratively developed and printed using UV-curable resin in an SLA 3D printer.

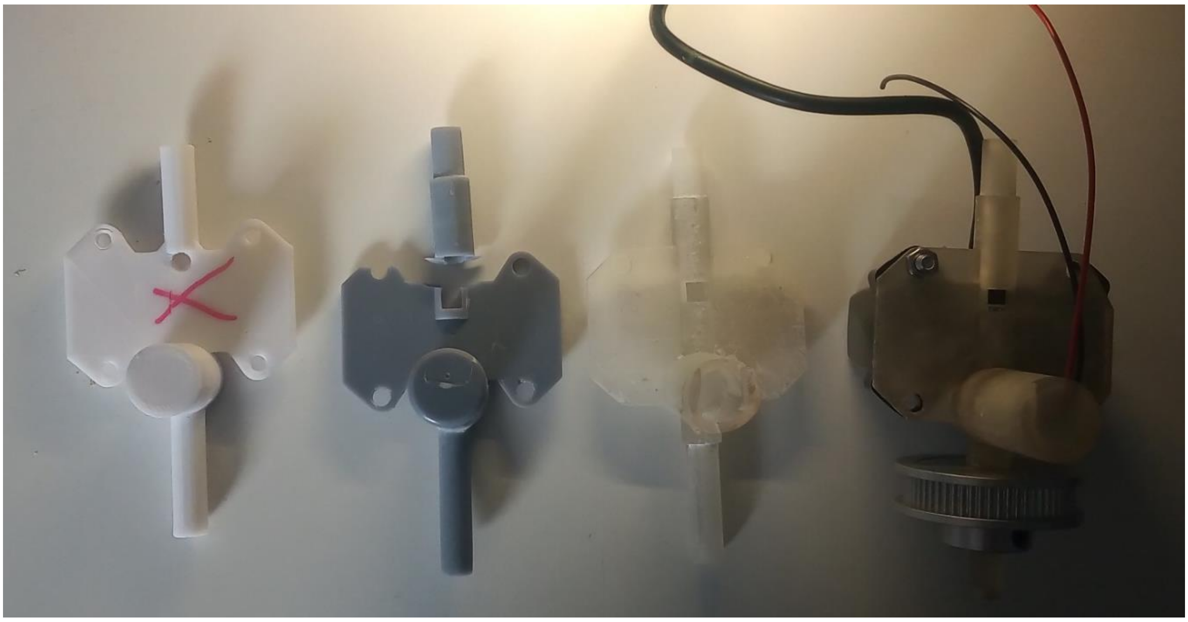


Figure 28: Iterations of head design (from left to right)

The movement of the head is controlled with a pair of pullies: a 60T pully on the head, and a 20T pully on the motor to give a 3:1 ratio.

All of the pullies and belt use the GT2 profile, commonly found in 3D printers and specifically chosen as the design prevents backlash.

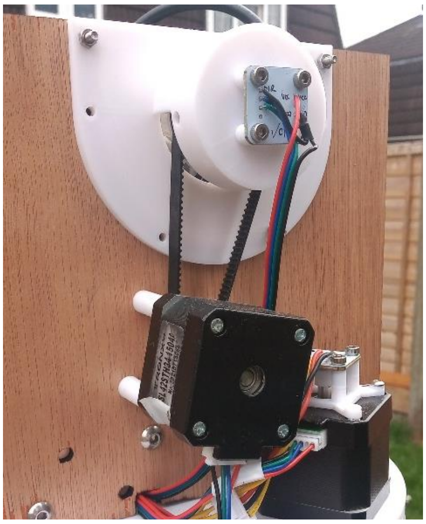


Figure 29: Altitude motor and pully

Display Housing

The original designs show the display as an integral part of the scanner body, however, if the user was to rotate the body of the sensor, then the display would also move, which could cause incorrect commands to be pressed on the touch screen.

To prevent this, it was deemed necessary to have the display detachable from the main body. For the purposes of simplicity, a wired connection was chosen.

The display housing also had to house the display carrier board, as well as house suitable location for the touch screen stylus, without the stylus jabbing any sensitive internal electronics.

When not in use, the display housing sits in a caddy that's affixed to the body. The rigidity of the 10-core cable prevents the display housing from falling out of the caddy.

Figure 30: Display housing before the display is installed

Miscellaneous Fixtures

In addition to the main components, there were also a number of smaller fixtures which formed crucial parts of the overall construction. These include, but are not limited to:

The battery holder.
Cable stays for both ends of the display cable.
Cable stay for the LiDAR sensor cable.
A mount for the power switch.
Various standoffs for the circuit board and altitude motor.

All of these components were printed in PLA plastic, and where possible, designed to fit existing fixing points.

An example of this is the cable stay used on the sensor head which utilises the existing nut and bolt fixing. This can be seen in Figure 31.

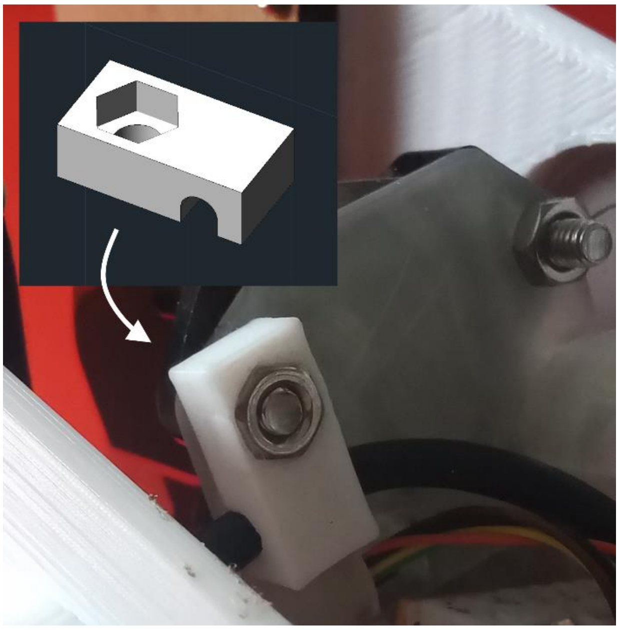


Figure 31: Cable stay used for LiDAR Sensor

Final Construction

Once all of the parts had been fabricated and fettled, the full scanner was constructed. The general order of construction was as follows:

1. Assemble head sub system, including the laser diode, LiDAR sensor, two bearings and pully.
2. Fit the elevation belt around the pully, temporarily hold by taping the belt together around the pully.
3. Fit the side panel over the head pully, feeding the belt through the hole.
4. Affix the azimuth pully to the azimuth motor and tighten grub screws.
5. Using four suitable standoffs, fit the azimuth motor to the ply board, ensuring that the belt goes over both pullies and is not loose.
6. Wire the slip ring through the head. Note that the cables have to be fed through individually before the socket is fitted.
7. Fit other side panel and slip ring; noting the location of the wire connections.
8. Mount the side panel and slipring construction to the other ply board.
9. Fix both ply boards together with the central block.
10. Attach the azimuth motor to the upper-base.
11. Fit the two AS5600 rotational encoders – remember to install the magnets on to the shafts beforehand.
12. Attach the motherboard with suitable standoffs.
13. Fix all motor and sensor wiring in place; routing cables in necessary voids under the central block.
14. Screw the upper-base to the central block from the underside.
15. Upturn the scanner and lay out the ball bearings and cage within the race of the upper-base.
16. Using the two idler pullies and the azimuth motor pully, fix the lower-base down, clamping the ball bearings in place. Ensure that the grub screws for the azimuth pully are tightened.
17. Feed the levelling screws through the upper-aluminium plate.
18. From below, fix the upper-aluminium plate to the underside of the lower-base.
19. Slide the levelling springs over the protruding levelling screws and slot the lower-aluminium plate through the corresponding holes.
20. Fix the lower-aluminium plate in place with the levelling knobs.
21. Attach the battery holder.
22. Glue the display caddy in place on the base.
23. Plug in the display, attach the display cable stay and switch holder.
24. Complete all final wiring, including switch wiring, head cabling and battery terminals.
25. Assuming that the microcontroller has been pre-programmed, the scanner can now be turned on and used.

A range of fixings were used throughout the project in a variation of different sizes. The table below notes the range of fixings needed.

Type of fixing	M3	M4	M5
Stainless button head hex drive	12mm 16mm 20mm 35mm Nut	12mm Nut	12mm 20mm
Stainless cap head hex drive	8mm		
Counter sunk flat head hex drive		45mm	12mm

Calibration & Sub-System Tests

Preface: Micro-Stepping Tests

In 2022 after noticing a 'pulsing' behaviour in the motors, a test was carried out to monitor the motion of the stepper motors while in micro-stepping mode.

This test consisted of manually sending commands to move the motor by a single micro-step, over a series of different Vref voltages, while recording a laser point on a perpendicular wall approximately 600mm away from the test rig.

These tests had minimal load on the motors, with the head measuring less than 12g in weight and being approximately 10mm from the centre of gravity.

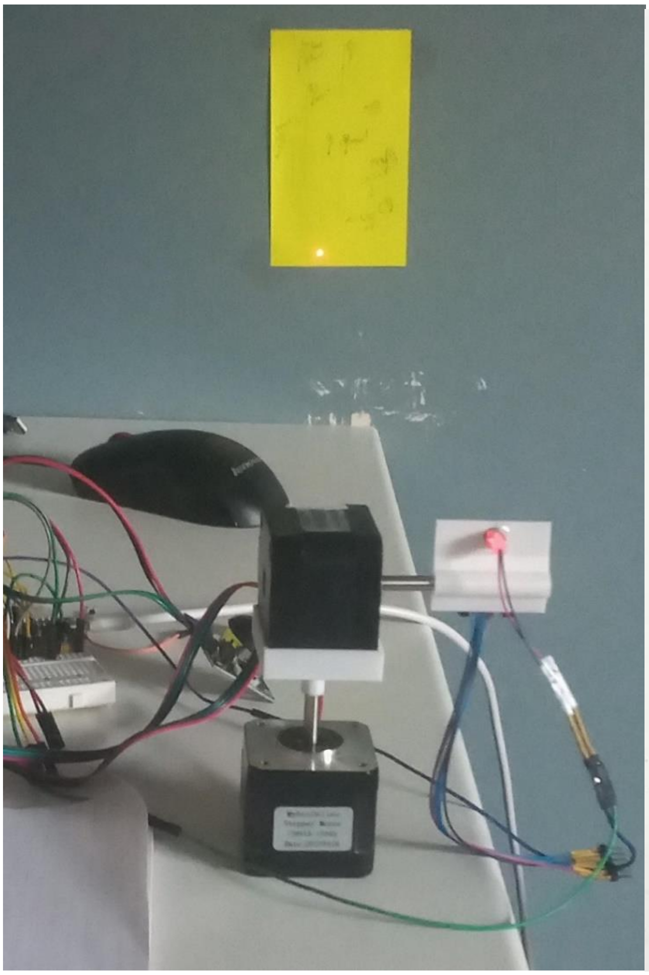


Figure 33: Test rig to measure microstep accuracy

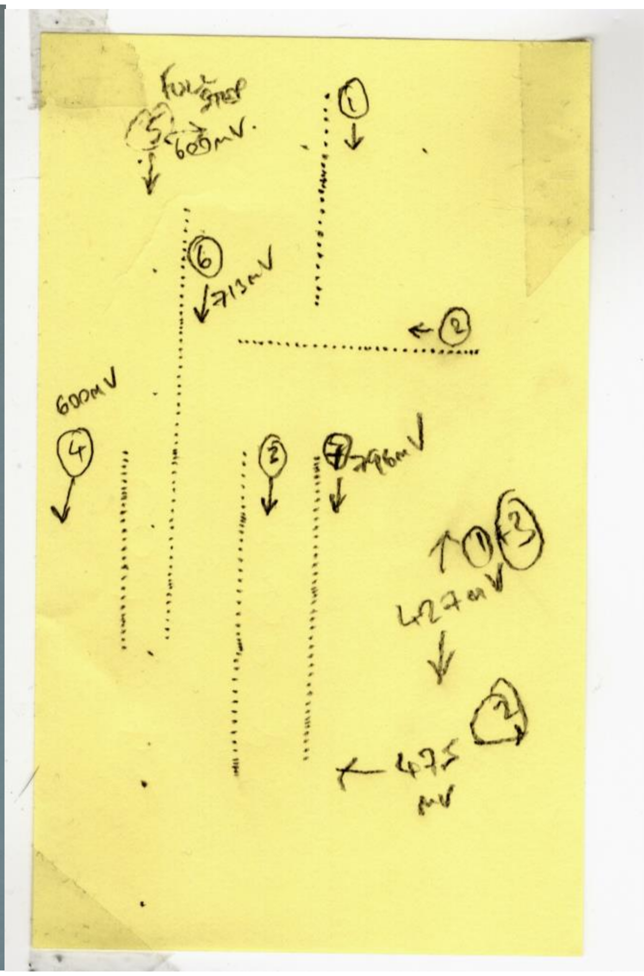


Figure 32: Results from microstep accuracy test

The results from this test noted that increasing the Vref did have a positive outcome, however, the pulsing artifact remained and the temperature of the stepper motor drivers. Reducing the microstep resolution to ½ or full step did completely mitigate the issues, however at the cost of rotational accuracy.

As such, it was deemed necessary to add the magnetic rotational sensors as a closed-loop feedback system to mitigate this motion problem.

Azimuth Motor and Sensor Calibration

As the motor registers a complete rotation as (16x200=) 3200 steps and the rotational sensor registers a complete rotation as 4096 segments, a two-part test jig was 3D printed with the magnet centrally located in the base and a rotational sensor fitted above. This sensor data was compared to the data from the azimuth sensor.

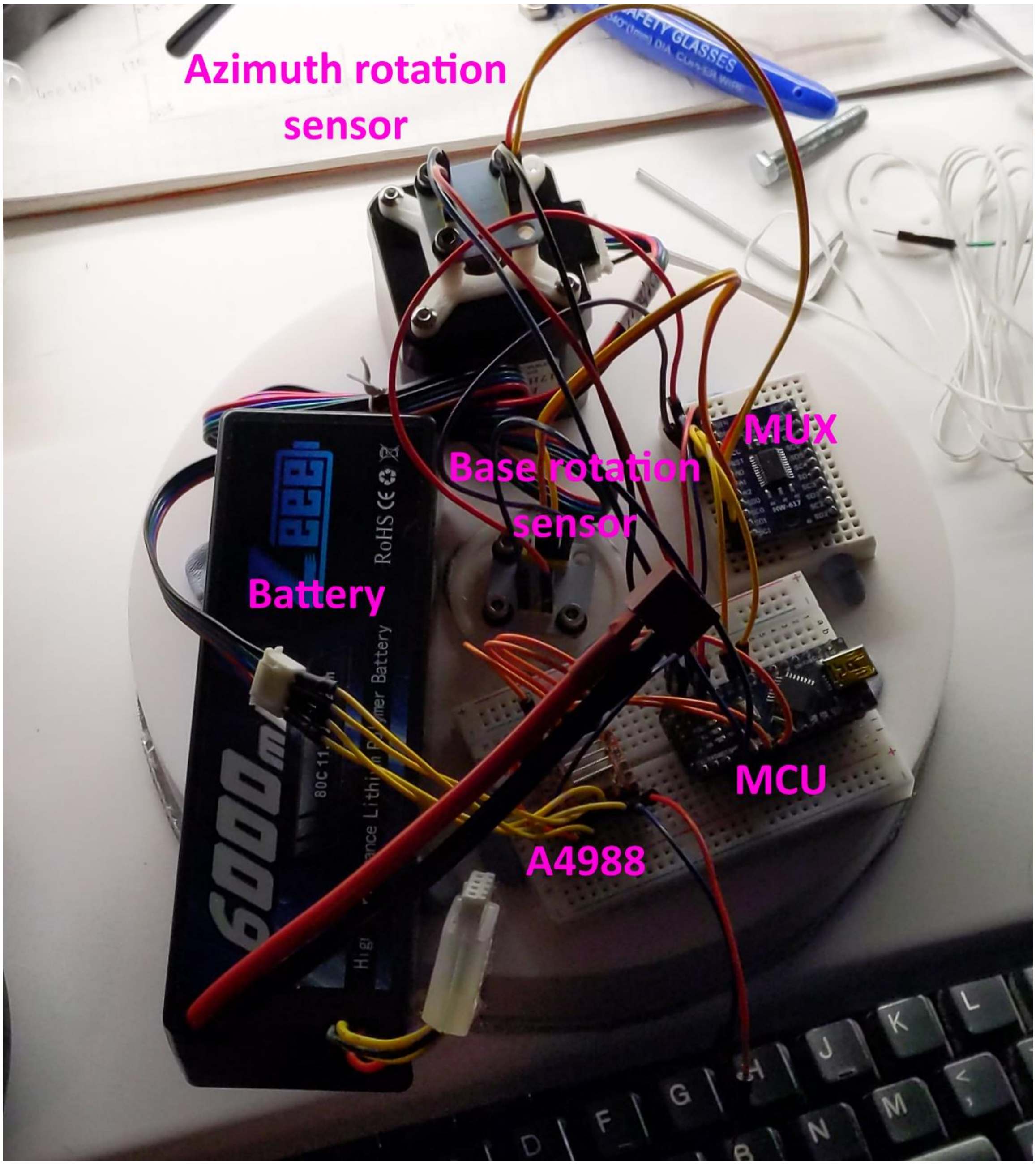


Figure 34: Test rig for base rotation

The motor speed was varied and the tests were recorded on Microsoft excel via the output from the serial monitor as noted below. The highlighted result is the required test result:

	5us step		50us step	
	as5600	motor step	as5600	motor step
measured	43866	34234	43763	34240
360deg equivalent	4096	3200	4096	3200
	10.70947	10.69813	10.68433	10.7

Figure 35: Excerpt of test data

Touch Screen Calibration

The touch sensor on the display is implemented using a resistive network which returns three values when touched: the strength of the touch and the relative x and y points. The raw data from this sensor does not match up with the display pixels, therefore the touch interface needs to be tested and calibrated.

The test consisted of the relevant screen being shown on the display and then the buttons on the screen were individually pressed with the raw data being recorded on the serial monitor. This data was then exported to Microsoft Excel and inserted into a graph to show the relative positions the touch sensor is sensing.

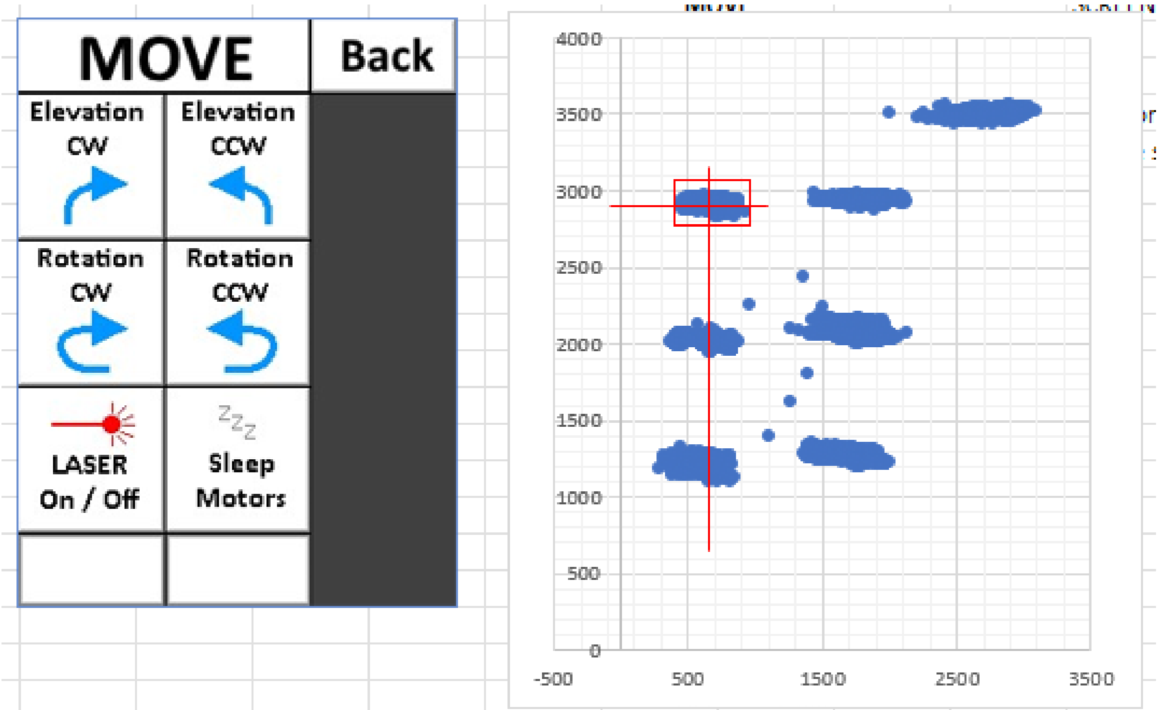


Figure 36: Screenshot showing the raw touch screen coordinates

LiDAR Calibration

During testing it was noted that the initial LiDAR readings were inaccurate and had a negative effect on the scan quality. This was investigated by carrying out a test where the LiDAR sensor was kept stationary and polled in quick succession.

The resulting graph demonstrated on the right shows that the sensor under-measures the distance for the first 800-1000 measurements before returning stable and correct measurements.

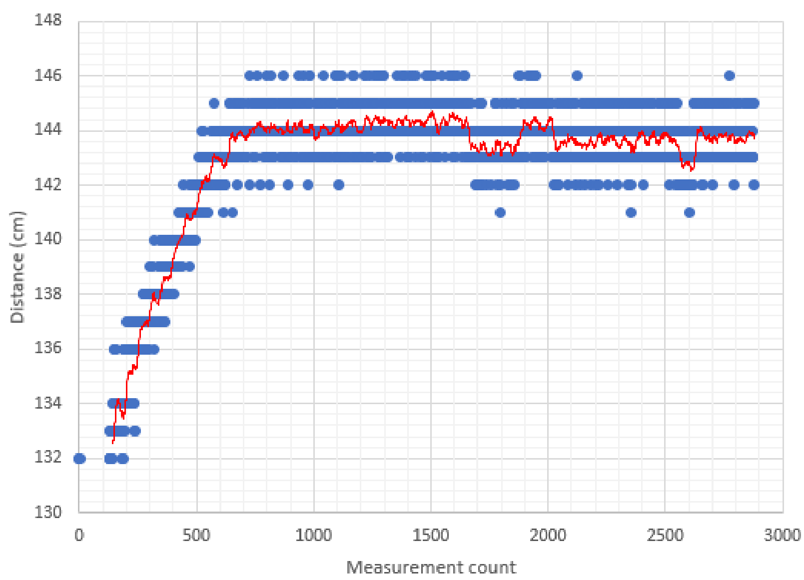


Figure 37: Graph showing the warm-up period of the LiDAR sensor

Software & User Interface Design

Preface

All the code for this project is written using C++ in the Arduino IDE. Various specialist libraries have been incorporated in to the code for handling all of the low-level interactions with the various sensors, including the following:

SPI.h for simplifying communications over the SPI bus.
SD.h for interfacing with the SD card.
TFT_eSPI.h has been used for controlling the touch display.
TCA9548.h for interfacing with the multiplexer.
AS5600.h for interfacing the magnetic rotary encoders.
LIDARLite_v3HP.h for interfacing the LiDAR sensor.

Due to the wiring onboard the microcontroller, it’s not possible to connect the battery power while the USB cable is plugged in. This means that while the batteries are powering the system, there can be no serial connection to the computer.

Point Cloud Output

All data collected by the scanner is to be saved to the on-board SD card. There are various competing point cloud data formats; these are broadly split in to two groups: ASCII text formats, or optimized binary formats.

Due to simplicity, the file format chosen was the .xyz format. This offers two main advantages: firstly, it is simple to implement and also universally compatible with CAD systems. The main drawbacks of the .xyz format are the lack of file compression leading to large file sizes, and the relative lack of metadata [ref 13]. Thankfully, the number of data points is relatively low, being in the order of thousands of points rather than millions of points, so the compression and file size issues are a moot point.

The .xyz format is simple to implement. Each line represents a single point which is positioned using three coordinates separated by spaces or tabs. Comments such as the scan time and number of points can be added to the file by appending them with a ‘#’ sign.

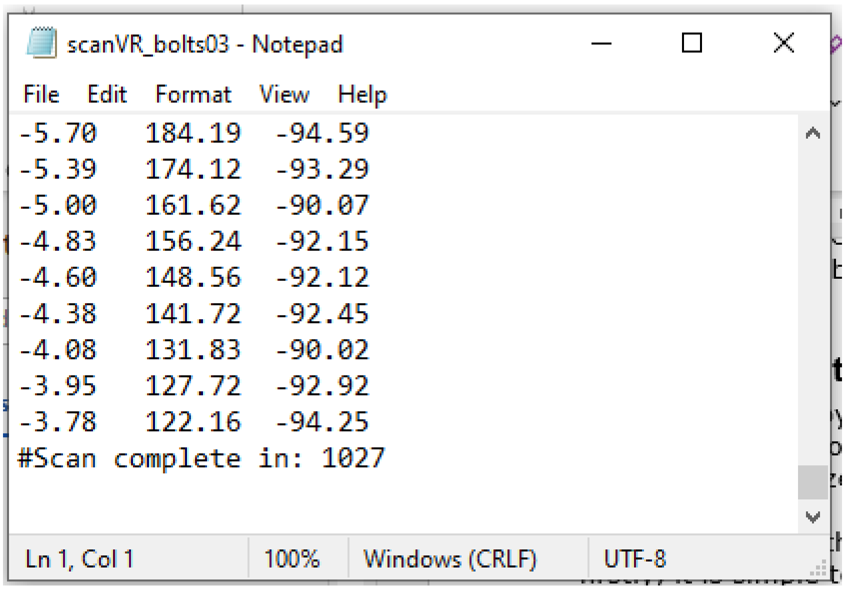
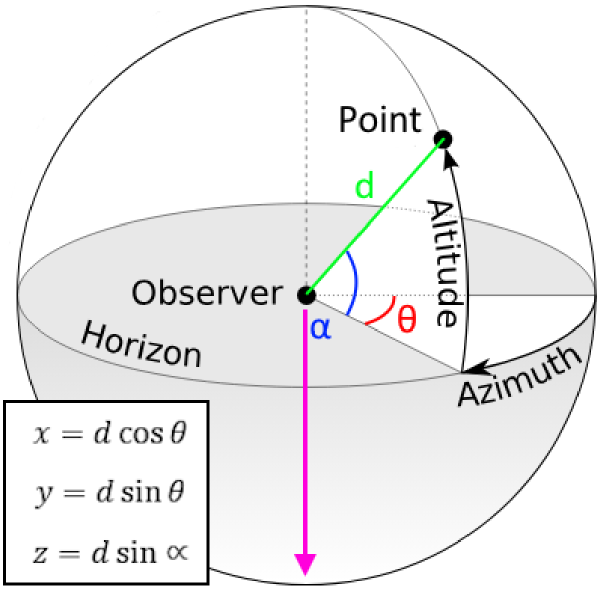


Figure 38: Example output of .xyz file

The other benefit to this format is the ability to pull the data into Microsoft Excel for further inspection and manipulation.

Onboard Calculations

The maths behind the generation of the x, y and z co-ordinates requires basic trigonometry as shown by the graphic to the side.



The value for ‘d’ is obtained from the LiDAR sensor, the value for ‘θ’ is obtained from the azimuth rotation sensor, and the value for ‘α’ is obtained from the altitude rotation sensor.

All calculations are done using double floating-point maths to increase the precision of the results from 7 decimal places to 15 decimal places. [ref 14]

The centre points of the scan head is deemed to be the origin point with the coordinates of 0,0,0.

Scan Algorithm

There are multiple ways for the scanner to survey the area. The initial concept spun the scanner about the central z axis while incrementally increasing the altitude. Due to the gear ratios of the azimuth motor, this approach would rove to be very slow.

As such, the movement of the scanner was to spin the altitude motor up and over the top dead centre (1) and then increment the azimuth motor (2) before returning the altitude motor up and over to the original side (4). This is repeated several times until the whole area has been scanned.

This method reduces the amount of motion the azimuth motor needs to travel as the base only needs to cover a 180-degree turn.

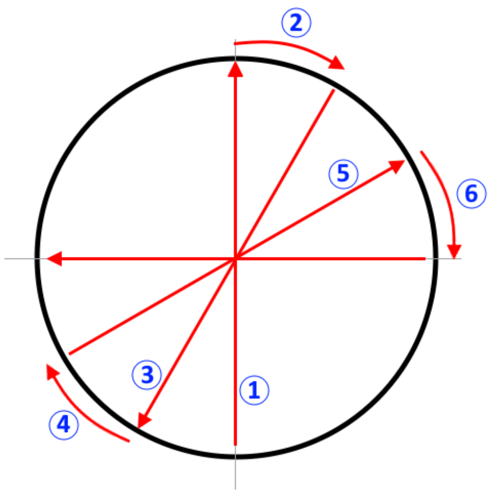


Figure 39: Scanner movement when viewed from above

In addition to this, the increment of the altitude motor is dynamically variable and based on the previous distance measured and the user resolution selection. This is to reduce the number of measurements taken of near-by objects and also increase the number of measurements for far-away objects.

The angle required to move is calculated as such:

$$\theta = tan^{-1}\left(\frac{Resolution}{Distance}\right)$$

Where the resolution is set at 10cm for low resolution scans, and 5cm for high resolution scans

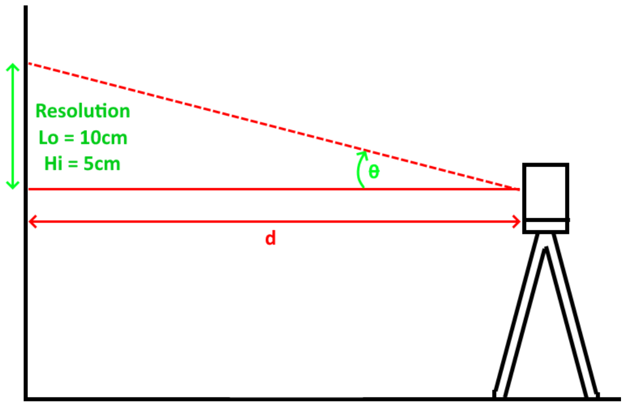


Figure 40: Diagram showing the dynamic altitude resolution

Graphic User Interface

The user interface has a menu structure that is two levels deep. The first top level is the menu page, all other pages are on the level below, each with a button allowing the user to go back to the top-level menu.

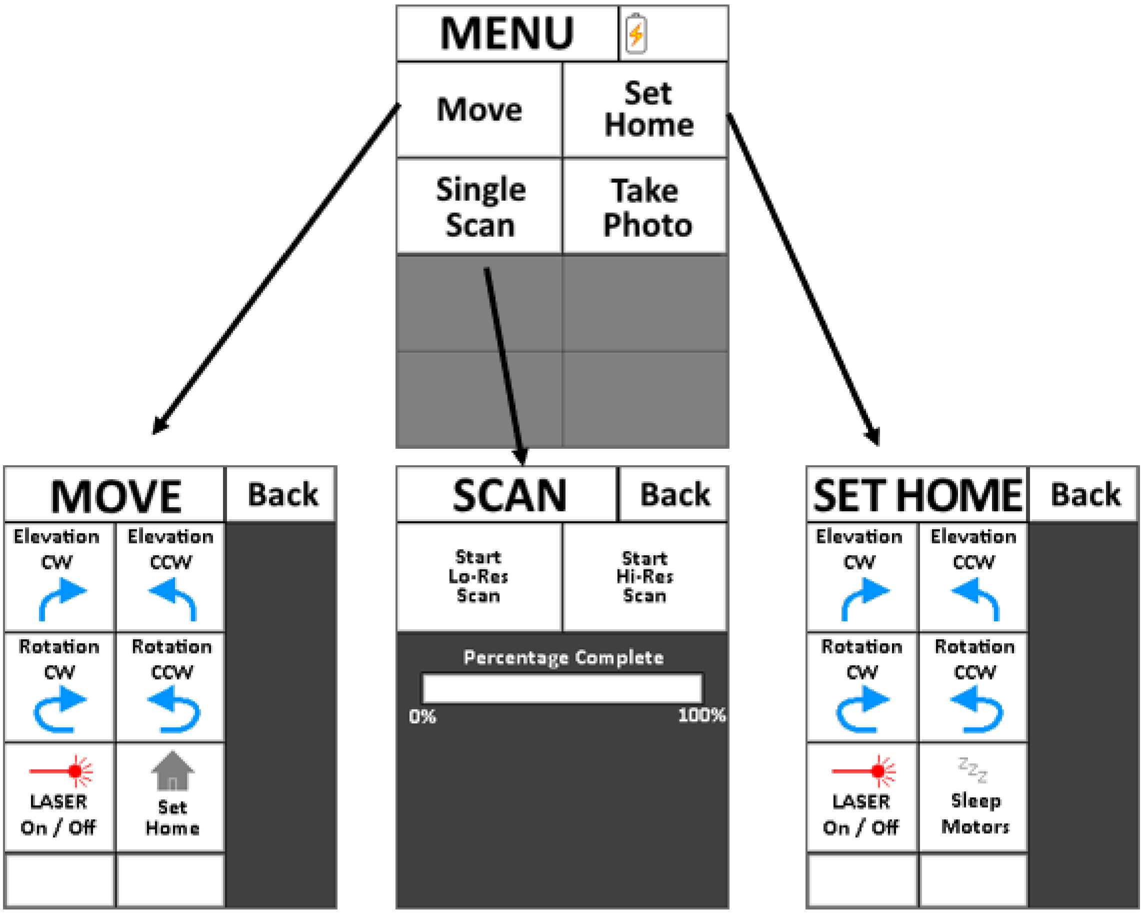


Figure 41: Structure of the user interface

All of the screens were designed in Paint.NET before being flattened and exported as .png files and converted to an RGB565 byte array using the online converter at http://rinkydinkelectronics.com/t_imageconverter565.php

Additional Feature: 'Photo' Mode

For the college presentation, a special 'photo' mode was implemented to demonstrate to the class. This takes a 160x80 pixel colourised depth map image and displays it to the screen. This mode does not use the rotational sensors, instead relying on relative position of the motors.

The small number is the time taken to complete the image in milliseconds (408788ms = 6min 49sec)

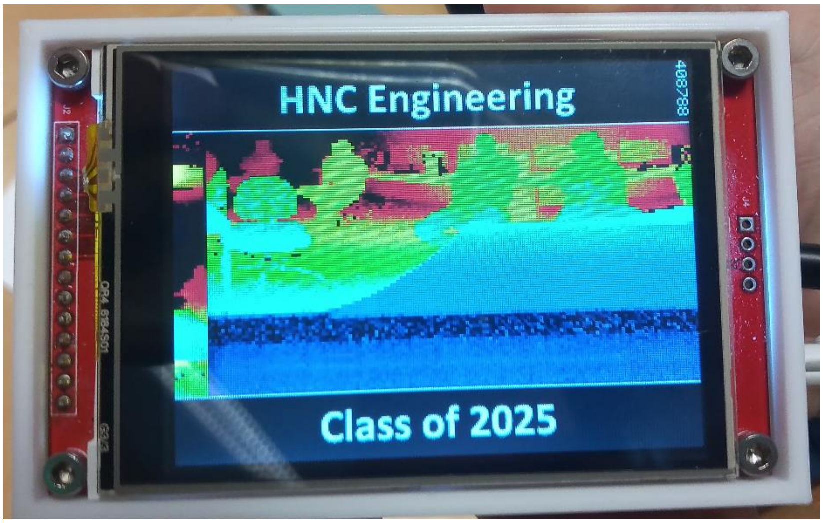


Figure 42: 'Photo' taken during the presentation

Current Results & Future Recommendations

Status of Project

The scanner is currently in the testing and software development phase, ironing out imperfections and other bugs. The current software is outputting coherent data which can be analysed. A copy of the current software code can be found in Technical Appendix A

Below is an example of a point cloud with an indicative real-world scene view to give a comparison (The cyan coloured line is to give a reference between the two images).

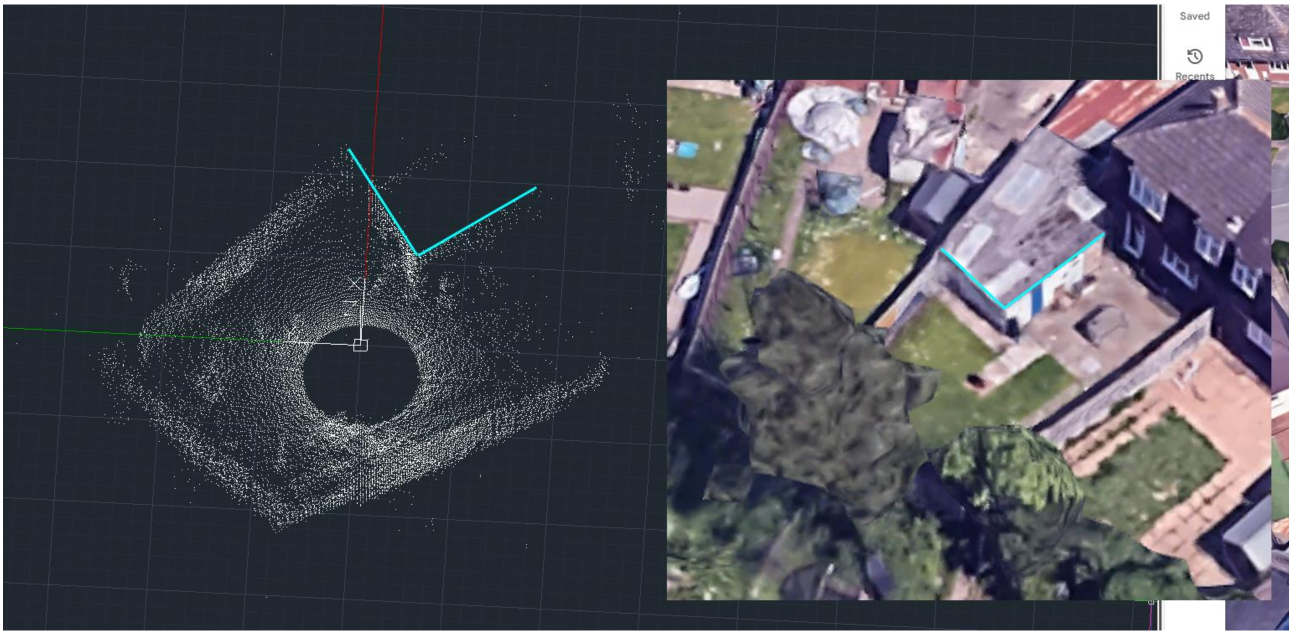


Figure 43: Point cloud (left) comparable 3D scene (right)

At the time of writing, the focus is on using MeshLab to process the data to convert the .xyz files in to a useable point cloud and mesh; an example of the mesh can be seen below.

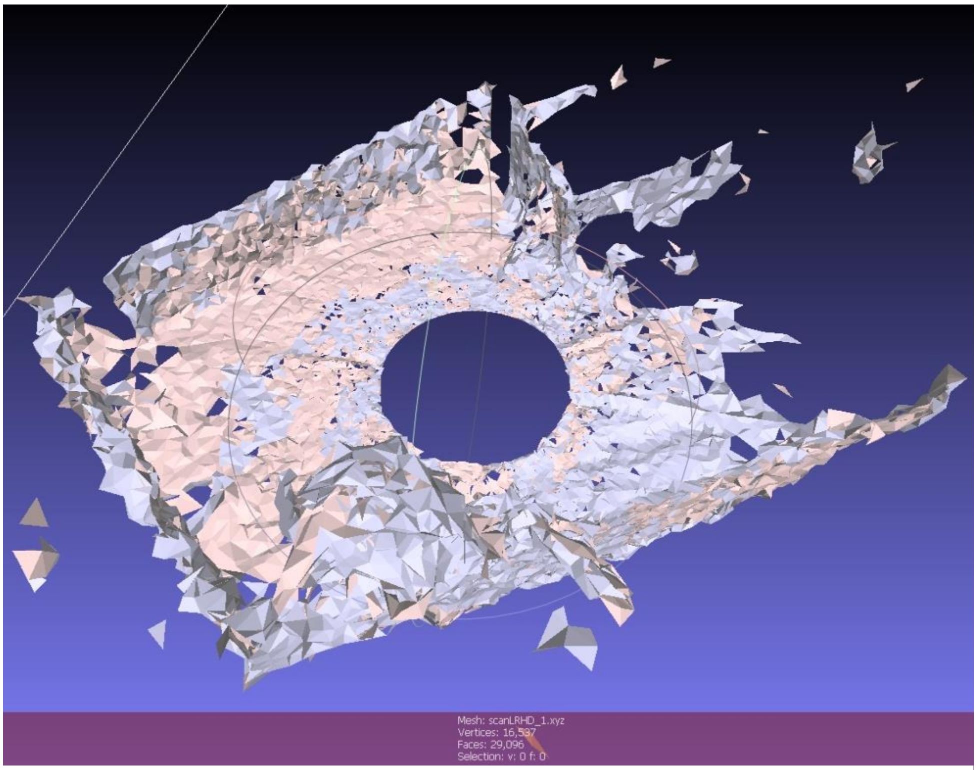


Figure 44: Mesh constructed from original point cloud

Mesh Rendering

The results are achieved in MeshLab using the following process:

Step 1: Import point cloud
Using the 'import' button from the top menu bar, select the relevant .xyz file. The keyboard shortcut for importing is CTRL+I

Step 2: Compute normal
Go to the 'Filters' menu, select 'point set' and then click on 'compute normal for point sets'. It is recommended to change the smoothing iteration to '3', however, smoothing can be applied after. See figure 45 below.

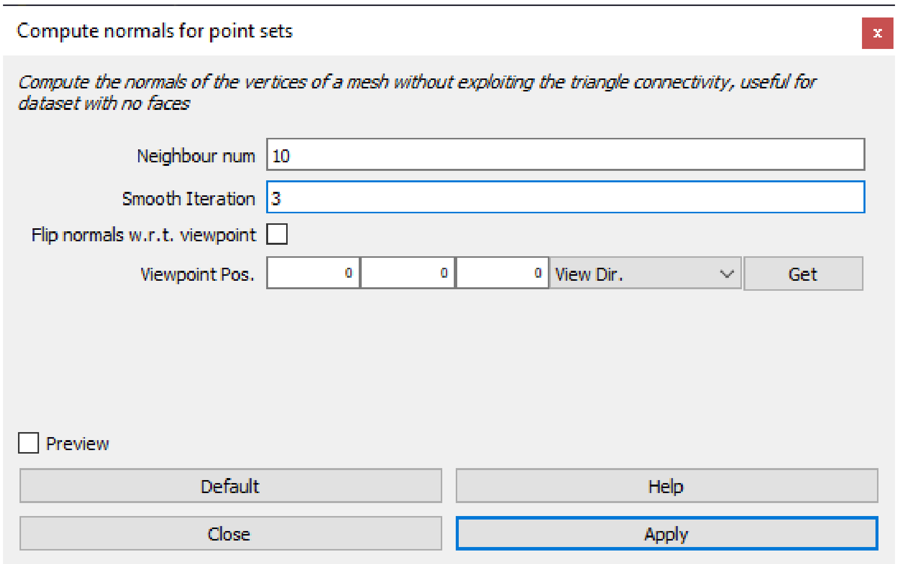


Figure 45: Settings for computing the normals for a point cloud

Step 3: Create mesh
Go to the 'Filters' menu, select 'remeshing, simplification and reconstruction', then select, 'surface reconstruction: ball pivoting'. It is recommended to change the world unit radius to 20 and reduce the clustering radius to 5%. See figure 46 below.

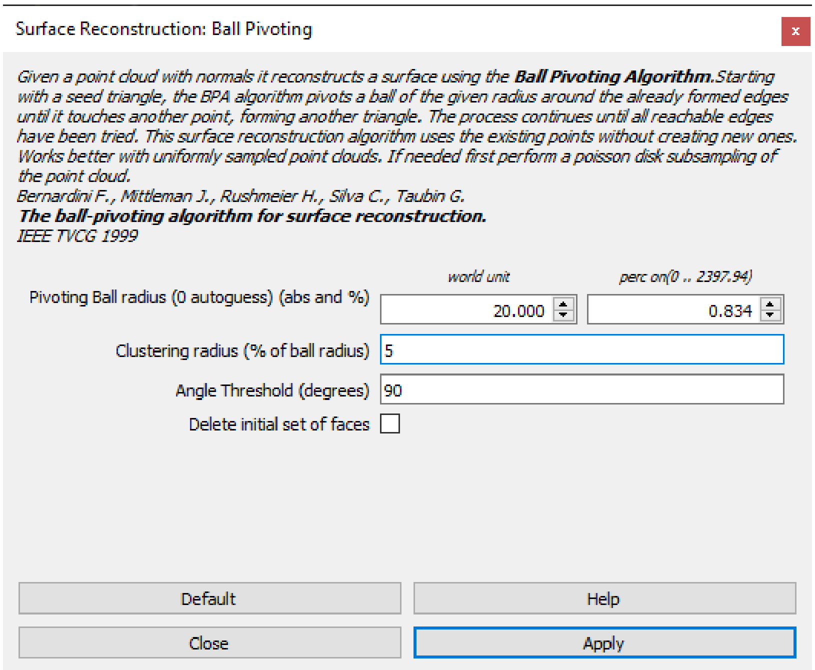


Figure 46: Settings for mesh construction

Current Results

At the time of writing; these are the current statistics and test results from the scanner. Please note that due to the variable azimuth resolution, the actual number of points and time taken will depend on site conditions. The below figures are provided based on a like-for-like conditions for a fair comparison.

<u>Low resolution scan:</u>
Time = 759 seconds
Points = 7,367
Points per second = 9.7

<u>High resolution scan:</u>
Time = 832 seconds
Points = 14,424
Points per second = 17.4

<u>Photo mode:</u>
Time = 409 seconds
Points = 12,800
Points per second = 31.3

Previous tests have yielded 12,000 points in 840seconds in low resolution mode, and 21,000 points in 1,020 seconds.

Discrediting outlying erroneous points, the maximum diagonal measurement is 19.139m. This is below the 40m diagonal required (20m radius).

Figure 47 shows the dimensional accuracy test using a Hilti PD4 laser measurer. The results of this test yielded a 0.153% error, as calculated below.

$$\frac{9mm\ error}{5901mm\ range} \times 100 = 0.153\%$$

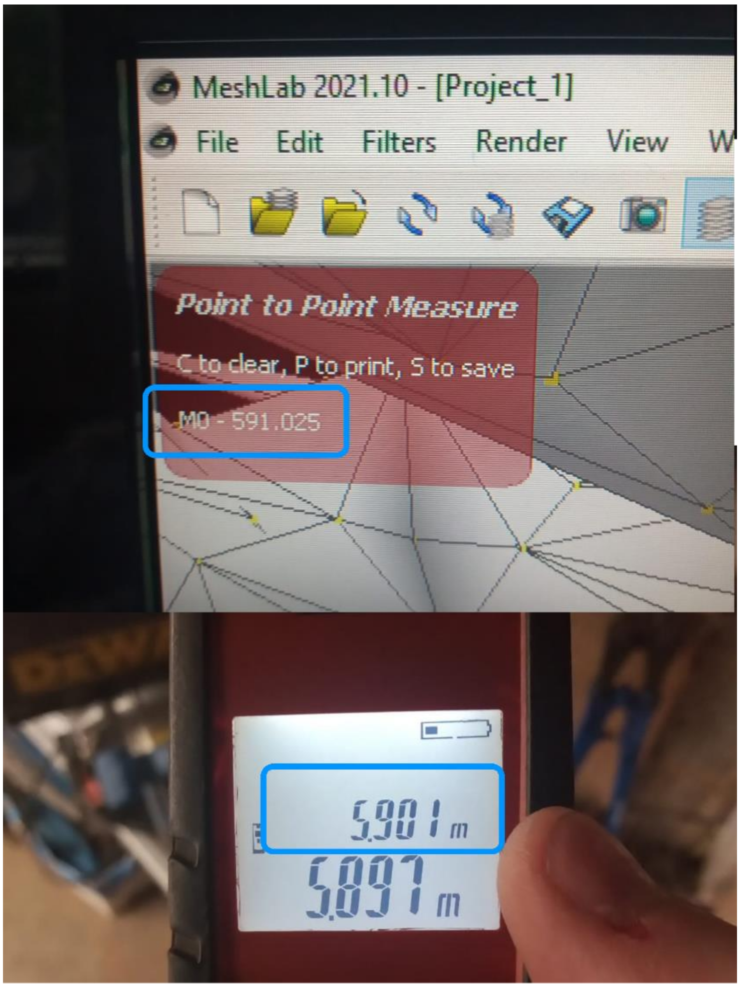


Figure 47: Results from Dimensional Accuracy test

Project Analysis & Evaluation

Bill of Materials & Cost Analysis

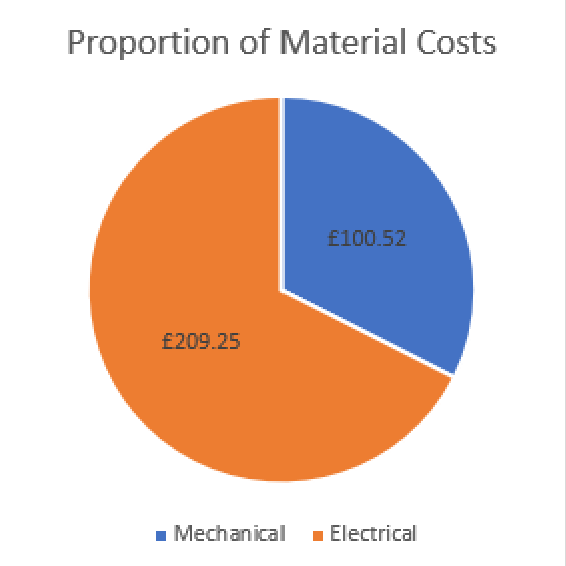
The costs of the project were monitored and tracked throughout the build on a Microsoft Excel spreadsheet.

As with any research and development project, there were a number of items purchased that were not implemented in the final build. The Bill of Materials is below:

Date	Description	Supplier	Cost	Comments
01/03/2022	6mm Aluminium plate	Ebay	£ 29.00	
22/04/2024	JST XH 6-10pin sockets	Ebay	£ 6.95	General stock
27/08/2024	AS5600 rotary encoder and multiplexer	Ebay	£ 12.73	
03/09/2024	GT2 timing belt and pullies	Ebay	£ 11.14	
21/10/2024	Garmin LiDAR Lite V3HP sensor	Ebay	£ 60.00	
23/10/2024	Countersunk machine screws	Ebay	£ 8.99	General stock
25/10/2024	Teensy 4.1 MCU	The Pi Hut	£ 33.80	
11/11/2024	Bubble level	Ebay	£ 3.11	
11/11/2024	Laser diode	Ebay	£ 5.99	
11/11/2024	PLA Filament (white) - 1Kg	Ebay	£ 12.22	General stock (used 781/1000g)
30/11/2024	Wire - 22AWG, black, red, yellow	Ebay	£ 12.42	General stock
14/12/2024	2x Double shaft NEMA17 Steppers	Ebay	£ 26.23	
16/12/2024	Slip ring, 6 wire	Ebay	£ 8.49	
07/01/2025	20x M5x40 screws	Ebay	£ 5.11	General stock
14/01/2025	Micro SD card adapter	Ebay	£ 3.98	
21/01/2025	Battery 11.1V 6000mah	Ebay	£ 35.99	Not used
21/01/2025	Battery charger	Ebay	£ 8.18	
23/01/2025	Timing pully, belt, shaft	Ebay	£ 17.79	
23/01/2025	688ZZ bearings	Ebay	£ 2.95	
26/01/2025	Levelling knobs and springs	Ebay	£ 3.05	
29/01/2025	Heatset threadded inserts	Ebay	£ 13.99	General stock - not used
30/01/2025	5x M4x45 screws	Ebay	£ 3.26	
24/03/2025	10 core wire	Ebay	£ 6.77	
24/03/2025	6 core wire	Ebay	£ 5.81	Miss-ordered: not used
31/03/2025	Toggle switch	Ebay	£ 3.99	Pack of 5; only 1 used
31/03/2025	4.5mm plywood	B&Q	£ 10.32	
08/04/2025	SLA Resin	Ebay	£ 18.00	General stock
08/04/2025	IPA	Ebay	£ 16.99	General stock
12/04/2025	2x 3S 11.1V lipo batteries	Ebay	£ 38.59	
18/04/2025	Mini cooling fan	Ebay	£ 2.81	Not used
22/04/2025	DC-DC voltage regulator	Ebay	£ 2.75	Not used
23/04/2025	Buck converter - 3.3V	Ebay	£ 3.90	
13/05/2025	Bucket	B&Q	£ 1.00	For transportation

The total amount of material purchases made throughout the project is £ 436.30 (inclusive of VAT). This is approximately split between £ 279.38 of electrical items and £ 156.92 of mechanical items.

This is not a fully accurate cost of the materials actually used for the scanner as there were a number of items not used, or partially used. Taking this fact in to account, the revised total for materials is approximately £309.77.



This total can be split in to two separate groups: electrical items such as sensors, batteries and wires, and mechanical items such as pullies, screws and printer filament/resin.

While the machinery used throughout this project was already accounted for, the breakdown of these costs are as follows:

£ 159.00 for FDM 3D printer
£ 206.92 for SLA 3D printer and wash/cure
£ 330.65 for 10W Laser cutter
£ 696.57 total for all machinery

Therefore, adding the revised cost of the materials to the cost of the machinery gives a grand total of £ 1,006.94 – exceeding the original budget by £ 6.94 (approximately 0.7%)

As this project was carried out during evenings and weekends, no renumeration was received for these hours of work. A fair estimate for the amount of time gone in to this project is in the region of 350 hours.

The estimated cost of the labour aspect of the project is heavily dependant on the hourly rate used. The rate for a junior engineer depends greatly on the employer and type of industry; these calculations are based on the average salary of £28,222 and a 40-hour working week to give an hourly rate. [ref 15]

Assuming a minimum wage of £12.21 per hour = £ 4,273.50
Assuming junior engineer wage of £13.57 per hour = £ 4,748.89

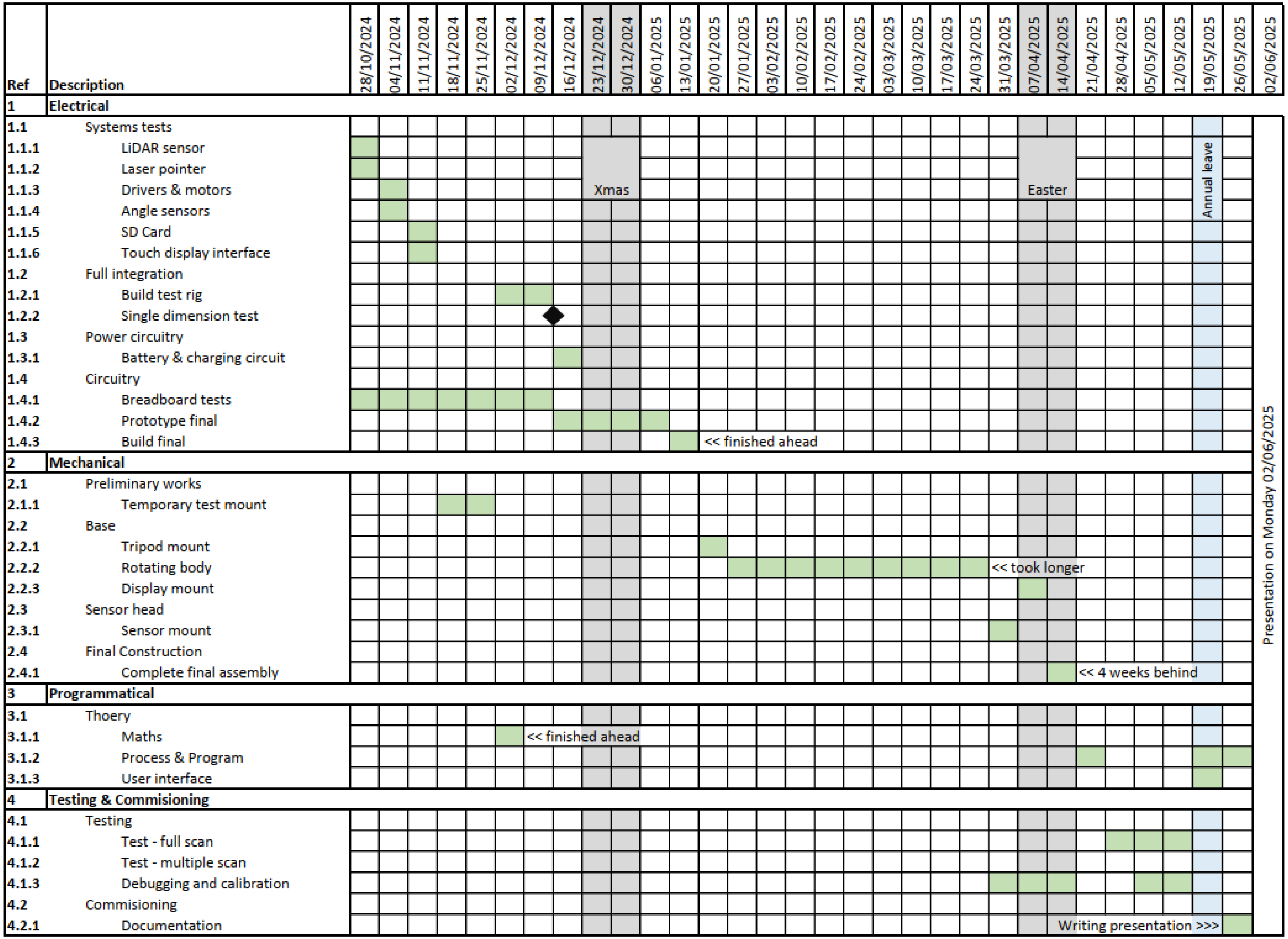
If the labour portion of the project was not free then it would form the largest portion of spending by a significant margin.

Program Analysis

To the right is a revised program up to the presentation date of 02/06/2025 complete with notes about the progress.

As the project matured, the original program went out of the window when it became apparent that it was not possible to carry out multiple tasks simultaneously. As a direct result of this, annual leave was booked for the week of the 19/05/2025 to concentrate on the project.

It is anticipated that the project will be completed in August 2025.



Technical Performance Analysis

The original project dimensions table has been appended to show how the results from the project compare to the initial requirements. Some dimensions have been removed as they were not applicable during the initial design phase.

Ref	Dimension	Requirement	Result
1	Functionality – What it should do	Minimum tolerance for accuracy is ±100mm over 20m range. Maximum time for a single scan to be no greater than 15mins. Ideally less.	Range = FAIL Results are 10m, requirement is 20m Accuracy = PASS Results are <0.2% error, requirement is <0.5% Time = PASS
3	Size	To fit on the tripod, the device should ideally not exceed 300mm cube.	PASS. Scanner measures 180mm diameter and 300mm high
4	Weight	Ideally, weight not to exceed 10kg.	PASS Scanner, including carry case weighs 2.8Kg
5	Aesthetics	No exposed wires or mechanisms.	FAIL Case not completed: there are exposed wires and mechanisms
6	Ergonomics	User interface to be intuitive, informative and easy to use.	PASS
7	Reliability	Have a fault-free and repeatable process. No wear on parts.	PASS In excess of 50 scans have been completed without failure
10	Recyclability	Where possible; pre-made sensors to be utilised.	PASS All parts are readily available and easily made with hobby-grade machinery
11	Compatibility	Hardware: Device should fit a standard surveyor’s tripod. Software: point cloud output to SD card for easy transfer.	PASS PASS
12	Efficiency	Power consumption to be as low as possible to increase battery time.	PASS
13	Cost	A fair estimate for materials is <£1,000.	FAIL Overbudget, albeit by a small amount.
14	Ethics (Compliancy & Legal)	Laser range finder is class 1 = safe. Laser pointer is class 3a = avoid direct exposure; do not view with optics.	PASS All health and safety items are compliant

Future Recommendations

To date, many of the objectives of this project have been met, however, there are some areas where development is ongoing. As such the main recommendations would be to continue development, focussing on three main items:

Increasing the range of the scanner
Decreasing the time taken to complete the scans
Implement the ability to stitch multiple scans together.

In addition to this, more research and testing is needed in to the correct methods of processing the scan to create reliable meshes.

Looking further forward, there may be the need to change out some of the electrical hardware to achieve the necessary gains. For example, utilising a microcontroller with multiple CPU cores (such as the ESP32) will enable the scanner to move while calculating the co-ordinates, rather than move THEN calculate.

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Slide 5

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Acknowledgements

This project would not have been possible without the support of my wife, employer, and Hereford, Ludlow and North Shropshire College.

Thank you.

Technical Appendices

Appendix A: Code

```
#include <SPI.h>
#include <SD.h>
#include <TFT_eSPI.h>
#include "TCA9548.h"
#include "AS5600.h"
#include <LIDARLite_v3HP.h>
#include "menuPNG.h"
#include "movePNG.h"
#include "setHomePNG.h"
#include "scanPNG.h"
#include "pcCompletePNG.h"
#include "photoFramePNG.h"

#define BACKGROUND_COLOUR 0x4208
#define UI_BLUE 0x04BF

const int batteryVoltagePin = A8;
const int laserPin = 34;
const int motorPin_elevDIR = 26;
const int motorPin_elevSTEP = 27;
const int motorPin_elevSLEEP = 28;
const int motorPin_rotDIR = 3;
const int motorPin_rotSTEP = 4;
const int motorPin_rotSLEEP = 5;
const int chipSelect = BUILTIN_SDCARD;

const int LIDAR_sensor = 1;  //channel 1 = Lidar
const int AS5600_rot = 2;  //channel 2 = rotational AS5600
const int AS5600_elev = 3;  //channel 2 = elevational AS5600

LIDARLite_v3HP myLidarLite;

PCA9546 MP(0x70);
AS5600 as5600_rot;
AS5600 as5600_elev;
File dataFile;

TFT_eSPI tft = TFT_eSPI();

uint16_t t_x = 0;
uint16_t t_y = 0;
uint16_t distance;  //lidar distance measure
int x_offset = 0;
int y_offset = 0;
int z_offset = 0;
double x, y, z, h;
long pointCount;
long scanTimeSeconds;
double resolution;

const float elevStepsPerRad = 1527.9;
const double radPerRot = 0.000143362;
const double radPerElev = 0.001534;
long rot_angle = 0;
long elev_angle = 0;

int screenID = 1;

bool laserState = false;
bool error_state = false;
bool motorState = true;
bool hiRes = false;
```

```
void setup() {
  Serial.begin(115200);
  Wire.begin();

  pinMode(batteryVoltagePin, INPUT);
  pinMode(motorPin_elevDIR, OUTPUT);
  pinMode(motorPin_elevSTEP, OUTPUT);
  pinMode(motorPin_elevSLEEP, OUTPUT);
  pinMode(motorPin_rotDIR, OUTPUT);
  pinMode(motorPin_rotSTEP, OUTPUT);
  pinMode(motorPin_rotSLEEP, OUTPUT);
  pinMode(laserPin, OUTPUT);

  digitalWrite(motorPin_elevDIR, LOW);
  digitalWrite(motorPin_elevSTEP, LOW);
  digitalWrite(motorPin_elevSLEEP, LOW); //logic low to sleep
  digitalWrite(motorPin_rotDIR, LOW);
  digitalWrite(motorPin_rotSTEP, LOW);
  digitalWrite(motorPin_rotSLEEP, LOW); //logic low to sleep
  digitalWrite(laserPin, LOW);

  tft.init();
  tft.setSwapBytes(true);
  tft.fillScreen(TFT_BLACK);
  tft.setTextColor(TFT_WHITE, TFT_BLACK);
  tft.setCursor(0, 0, 2);
  tft.println("Loading...");
  delay(500);

  loadSequence();

  delay(500);
  goBackToMenu();
  Serial.println("x, y");
}
/////////////////////////////////////////////////////////////////////////////////////
void loop() {
  if (tft.getTouchRawZ() > 600) {
    tft.getTouchRaw(&t_x, &t_y);
    Serial.print(t_x);   Serial.print(", ");   Serial.println(t_y);
    findClosestButton(t_x, t_y, screenID);
    //delay(50);   //debounce screen touch
  }

  if (laserState) {
    digitalWrite(laserPin, HIGH);
  } else {
    digitalWrite(laserPin, LOW);
  }

}
/////////////////////////////////////////////////////////////////////////////////////
void loadSequence() {
  if (SD.begin(chipSelect)) {
    tft.println("SD hardware ok");
  } else {
    tft.println("SD FAIL");
    error_state = true;
  }
  delay(200);

  dataFile = SD.open("scanVR.xyz", FILE_WRITE);

  if (!dataFile) {
    tft.println("Failed to create file - check if SD card is present");
    error_state = true;
  } else {
    tft.println("SD card ok");
  }
  delay(200);
```

```
  if (MP.begin() == false) {
    tft.println("Multiplexer error");
    error_state = true;
  } else {
    tft.println("Multiplexer OK");
  }
  delay(200);

  MP.selectChannel(LIDAR_sensor);
  myLidarLite.configure(0);

  MP.selectChannel(AS5600_rot);
  if (!as5600_rot.begin(4)) {  //  set direction pin.
    error_state = true;
    tft.println("Rotation sensor FAILED");
  } else {
    tft.println("Rotation sensor OK");
  }
  as5600_rot.setDirection(AS5600_CLOCK_WISE);
  delay(200);

  MP.selectChannel(AS5600_elev);
  if (!as5600_elev.begin(4)) {  //  set direction pin.
    error_state = true;
    tft.println("Elevation sensor FAILED");
  } else {
    tft.println("Elevation sensor OK");
  }

  as5600_elev.setDirection(AS5600_CLOCK_WISE);

  if (error_state) {
    //  while (1);
  }
}
/////////////////////////////////////////////////////////////////////////////////////

void findClosestButton(int _tx, int _ty, int _screenID) {

  switch (_screenID) {

    case 1: //menu
      delay(100);
      if (_tx > 2000) {
        if (_ty > 2700) {
          screenID = 3; //set home
          tft.pushImage(0, 0, 240, 320, setHomePNG);
          digitalWrite(motorPin_rotSLEEP, HIGH);
          digitalWrite(motorPin_elevSLEEP, HIGH);
        } else {
          //take photo
          tft.pushImage(0, 0, 240, 320, photoFramePNG);
          takePhoto();
        }
      } else if (_ty < 2400) {
        screenID = 4; //single scan
        tft.pushImage(0, 0, 240, 320, scanPNG);
      } else {
        screenID = 2; //move
        digitalWrite(motorPin_rotSLEEP, HIGH);
        digitalWrite(motorPin_elevSLEEP, HIGH);
        tft.pushImage(0, 0, 240, 320, movePNG);
      }
      break;

    case 2: //move
      if (_ty > 3400) {
        goBackToMenu();
      } else if (_tx < 1000) {
```

```
      if (_ty < 1400) {
        Serial.println("laser");
        laserState = !laserState;
        delay(100);
        tft.fillRect(5, 285, 72, 30, TFT_WHITE);
        tft.setCursor(10, 290, 2);
        tft.setTextColor(TFT_RED, TFT_WHITE);
        if (laserState) {
          tft.print("LASER ON");
        } else {
          tft.print("LASER off");
        }
      } else if (_ty > 2700) {
        Serial.println("elev CW");
        step_elevCW(1);
      } else {
        Serial.println("rot cw");
        step_rotCW(1);
      }
    } else if (_tx > 1200) {
      if (_ty < 1400) {
        Serial.println("sleep");
        motorState = !motorState;
        delay(100);
        tft.fillRect(85, 285, 72, 30, TFT_WHITE);
        tft.setCursor(85, 285, 2);
        tft.setTextColor(TFT_BLACK, TFT_WHITE);
        if (motorState) {
          tft.print("Motors OFF");
          digitalWrite(motorPin_elevSLEEP, LOW);
          digitalWrite(motorPin_rotSLEEP, LOW);
        } else {
          tft.print("Motors ON");
          digitalWrite(motorPin_elevSLEEP, HIGH);
          digitalWrite(motorPin_rotSLEEP, HIGH);
        }
      } else if (_ty > 2700) {
        Serial.println("elev CCW");
        step_elevCCW(1);
      } else {
        Serial.println("rot ccw");
        step_rotCCW(1);
      }
    }

    break;

  case 3: //set home
    if (_ty > 3400) {

      goBackToMenu();
    } else if (_tx < 1000) {
      if (_ty < 1400) {
        Serial.println("laser");
        laserState = !laserState;
        delay(100);
        tft.setCursor(10, 290, 2);
        tft.setTextColor(TFT_RED, TFT_WHITE);
        if (laserState) {
          tft.print("LASER ON");
        } else {
          tft.print("LASER off");
        }
      } else if (_ty > 2700) {
        Serial.println("elev CW");
        step_elevCW(1);
      } else {
        Serial.println("rot cw");
        step_rotCW(1);
      }
```

```
      } else if (_tx > 1200) {
        if (_ty < 1400) {
          Serial.println("set home");
          setHome();
        } else if (_ty > 2700) {
          Serial.println("elev CCW");
          step_elevCCW(1);
        } else {
          Serial.println("rot ccw");
          step_rotCCW(1);
        }
      }
      break;

    case 4: //scan
      delay(100); //debounce
      if (_ty > 3400) {
        screenID = 1; //back to menu
        goBackToMenu();
      } else if (_tx > 2000) {
        //hi res scan
        tft.setTextColor(TFT_WHITE, BACKGROUND_COLOUR);
        tft.setCursor(10, 130, 2);
        tft.println("Starting high resolution scan");
        hiRes = true;
        delay(1000);
        tft.pushImage(0, 121, 240, 70, pcCompletePNG);
        singleScan();
        tft.setCursor(5, 195, 2);
        tft.print(pointCount);    tft.print(" points");
        tft.setCursor(5, 215, 2);
        tft.print("Scan completed in ");    tft.print(scanTimeSeconds);   tft.print("
seconds");
      } else {
        //lo res scan
        tft.setTextColor(TFT_WHITE, BACKGROUND_COLOUR);
        tft.setCursor(10, 130, 2);
        tft.println("Starting low resolution scan");
        hiRes = false;
        delay(1000);
        tft.pushImage(0, 121, 240, 70, pcCompletePNG);
        singleScan();
        tft.setCursor(5, 195, 2);
        tft.print(pointCount);    tft.print(" points");
        tft.setCursor(5, 215, 2);
        tft.print("Scan completed in ");    tft.print(scanTimeSeconds);   tft.print("
seconds");
      }
      break;
  }
}
/////////////////////////////////////////////////////////////////////////////////////
void setHome() {

  tft.setCursor(165, 50, 1);
  tft.setTextColor(TFT_WHITE, BACKGROUND_COLOUR);
  tft.println("Homing...");

  //zero sensor
  MP.selectChannel(AS5600_elev);
  as5600_elev.resetCumulativePosition();
  MP.selectChannel(AS5600_rot);
  as5600_rot.resetCumulativePosition();

  MP.selectChannel(LIDAR_sensor);

  for (int h = 0; h < 1400; h++) {
    myLidarLite.waitForBusy();
    myLidarLite.takeRange();
    myLidarLite.waitForBusy();
```

```
    distance = myLidarLite.readDistance();
  }

  z_offset = distance;
  tft.setCursor(165, 62, 1);
  tft.print("Complete.");
  tft.setCursor(165, 74, 1);
  tft.print(z_offset);
  delay(2500);
  goBackToMenu();

}
/////////////////////////////////////////////////////////////////////////////////////
void singleScan() {

  long scanStartTime = millis();

  digitalWrite(laserPin, LOW);
  delay(500);
  //move out of dead zone
  step_elevCW(1200);

  //remove backlash
  step_rotCW(20);

  /*  //stabalise LiDAR readings
    MP.selectChannel(LIDAR_sensor);

    for (int h = 0; h < 1400; h++) {
      myLidarLite.waitForBusy();
      myLidarLite.takeRange();
      myLidarLite.waitForBusy();
      distance = myLidarLite.readDistance();
      }   */

  //begin half rotation
  for (int s = 0; s < 50; s++) {
    tft.setCursor(0, 195, 1);
    //forward pass
    MP.selectChannel(AS5600_rot);
    rot_angle = as5600_rot.getCumulativePosition();   //rotation measure the same for
whole pass

    while (elev_angle < 4608) {
      //take xyz measurement
      takeMeasurement();
      //calculate next point;
      int stepsToTake = calculateNextPoint();
      step_elevCW(stepsToTake);
    }

    //rotate base and update percentage bar
    step_rotCW(171);
    tft.fillRect(20, 152, 2 * ((2 * s) + 1), 18, UI_BLUE);

    //back pass
    MP.selectChannel(AS5600_rot);
    rot_angle = as5600_rot.getCumulativePosition();   //rotation measure the same for
whole pass

    while (elev_angle > 1536) {
      //take xyz measurement
      takeMeasurement();
      //calculate next point;
      int stepsToTake = calculateNextPoint();
      step_elevCCW(stepsToTake);
    }

    //rotate base and update percentage bar
    step_rotCW(171);
```

```
    tft.fillRect(20, 152, 2 * ((2 * s) + 2), 18, UI_BLUE);

  }
  //return rotation to home
  step_rotCCW(17120);
  long scanTime = millis() - scanStartTime;
  scanTimeSeconds = scanTime / 1000;

  String dataString = "";

  dataString += String("#Scan complete in: ");
  dataString += String(scanTimeSeconds);

  dataFile.println(dataString);
  dataFile.flush();

}
/////////////////////////////////////////////////////////////////////////////////////
void takeMeasurement() {

  MP.selectChannel(LIDAR_sensor);
  myLidarLite.waitForBusy();
  myLidarLite.takeRange();
  myLidarLite.waitForBusy();
  distance = myLidarLite.readDistance();

  if (distance < 2000) {     //allow anything under 20m
    pointCount++;

    MP.selectChannel(AS5600_elev);
    elev_angle = as5600_elev.getCumulativePosition();
    elev_angle = elev_angle + 1024;

  //  tft.setCursor(0, 195, 1);
  //  tft.print("raw elevation = ");    tft.println(elev_angle);

    h = distance * cos(elev_angle * radPerElev);
    x = h * sin(rot_angle * radPerRot);
    y = h * cos(rot_angle * radPerRot);
    z = -distance * sin(elev_angle * radPerElev);

    z = z + z_offset;

    String dataString = "";

    dataString += String(x);
    dataString += String("\t");
    dataString += String(y);
    dataString += String("\t");
    dataString += String(z);

    dataFile.println(dataString);
    dataFile.flush();
  }

}
/////////////////////////////////////////////////////////////////////////////////////
int calculateNextPoint() {

  if (hiRes) {
    resolution = 5.0;
  } else {
    resolution = 10.0;
  }
  double tanAngle = atan2(resolution, distance);    //reduce the '10' to increase the
resolution
  // tft.print("atan2 of 10/"); tft.print(distance);  tft.print(" = ");
tft.println(tanAngle);
  int _stepsToTake = int(tanAngle * elevStepsPerRad);
  if (_stepsToTake > 300) {
```

```
    return 300;
  } else {
    return _stepsToTake;
  }
}
////////////////////////////////////////////////////////////////////////////////////////
void goBackToMenu() {
  delay(100); //debounce
  screenID = 1;
  tft.pushImage(0, 0, 240, 320, menuPNG);
  int rawAnalog = analogRead(batteryVoltagePin);
  float voltage = (0.0135 * rawAnalog) + 0.0855;

  tft.setCursor(185, 10, 2);
  if (voltage < 11.25) {
    tft.setTextColor(TFT_RED, TFT_WHITE);
  } else if (voltage > 11.5) {
    tft.setTextColor(TFT_GREEN, TFT_WHITE);
  } else {
    tft.setTextColor(TFT_ORANGE, TFT_WHITE);
  }
  tft.print(voltage); tft.print("V");
}
////////////////////////////////////////////////////////////////////////////////////////
void takePhoto() {

  long photoStartTime = millis();
  digitalWrite(laserPin, LOW);
  digitalWrite(motorPin_elevSLEEP, HIGH);
  digitalWrite(motorPin_rotSLEEP, HIGH);
 // tft.fillScreen(TFT_BLACK);
  MP.selectChannel(LIDAR_sensor);
  step_rotCCW(7680);
  step_elevCW(1080);

  //FAST PHOTO CODE
  int pix_y;
  int pix_x;
  uint16_t pix_colour;

  for (int mod = 0; mod < 80; mod ++) {
    pix_y = (320 - ((4 * mod) + 2));
    for (int down_row = 0; down_row < 80; down_row++) {
      //scan down one column
      myLidarLite.waitForBusy();
      myLidarLite.takeRange();
      myLidarLite.waitForBusy();
      distance = myLidarLite.readDistance();
      pix_colour = getColour(distance);

      pix_x = ((down_row * 2) + 40);
      tft.fillRect(pix_x, pix_y, 2, 2, pix_colour);
      step_elevCCW(27);
    }
    //shift to the next column
    step_rotCW(71);
    pix_y = (320 - ((4 * mod) + 4));
    for (int up_row = 0; up_row < 80; up_row++) {
      //scan up on column
      step_elevCW(27);
      myLidarLite.waitForBusy();
      myLidarLite.takeRange();
      myLidarLite.waitForBusy();
      distance = myLidarLite.readDistance();
      pix_colour = getColour(distance);

      pix_x = (198 - (up_row * 2));
      tft.fillRect(pix_x, pix_y, 2, 2, pix_colour);

    }
```

```
    //shift to the next column
    step_rotCW(71);
  }

  tft.setCursor(0, 0, 1);
  tft.setTextColor(TFT_WHITE, TFT_BLACK);
  long photoTime = millis() - photoStartTime;
  tft.println(photoTime);

  digitalWrite(motorPin_elevSLEEP, LOW);
  digitalWrite(motorPin_rotSLEEP, LOW);
  while (1);
}

////////////////////////////////////////////////////////////////////////////////////
uint16_t getColour(int _dist) {

  uint16_t distanceColour;

  unsigned int R = 0;
  unsigned int G = 0;
  unsigned int B = 0;

  if (_dist > 0) {
    //black - blue
    R = 0;
    B = map(_dist, 0, 63, 0, 31);
    G = 0;
  }
  if ((_dist > 63) && (_dist < 128)) {
    //blue - cyan
    R = 0;
    B = 31;
    G = map(_dist, 63, 127, 0, 31);
  }
  if ((_dist > 127) && (_dist < 192)) {
    //cyan - green
    R = 0;
    B = map(_dist, 127, 191, 31, 0);
    G = 31;
  }
  if ((_dist > 191) && (_dist < 256)) {
    //green - yellow
    R = map(_dist, 191, 255, 0, 31);
    B = 0;
    G = 31;
  }
  if ((_dist > 255) && (_dist < 320)) {
    //yellow - red
    R = 31;
    B = 0;
    G = map(_dist, 255, 319, 31, 0);
  }
  if ((_dist > 319) && (_dist < 384)) {
    //red - black
    R = map(_dist, 319, 383, 31, 0);
    B = 0;
    G = 0;
  }
  if (_dist > 383) {
    //black
    R = 0;
    B = 0;
    G = 0;
  }
  distanceColour = ((R << 11) + (G << 6) + (B));

  return distanceColour;
}
```

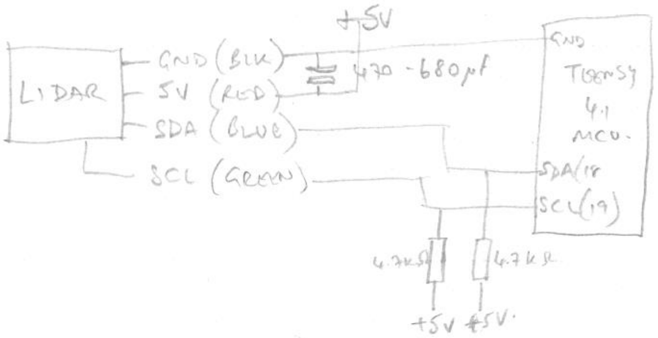
```
////////////////////////////////////////////////////////////////////////////////////

void step_elevCCW(int _noOfSteps) {

  for (int steps = 0; steps < _noOfSteps; steps ++) {
    digitalWrite(motorPin_elevDIR, HIGH);
    digitalWrite(motorPin_elevSTEP, HIGH);
    delayMicroseconds(400);
    digitalWrite(motorPin_elevSTEP, LOW);
    delayMicroseconds(400);
  }
}
////////////////////////////////////////////////////////////////////////////////////

void step_elevCW(int _noOfSteps) {

  for (int steps = 0; steps < _noOfSteps; steps ++) {
    digitalWrite(motorPin_elevDIR, LOW);
    digitalWrite(motorPin_elevSTEP, HIGH);
    delayMicroseconds(400);
    digitalWrite(motorPin_elevSTEP, LOW);
    delayMicroseconds(400);
  }

}
////////////////////////////////////////////////////////////////////////////////////

void step_rotCW(int _noOfSteps) {

  for (int steps = 0; steps < _noOfSteps; steps ++) {
    digitalWrite(motorPin_rotDIR, LOW);
    digitalWrite(motorPin_rotSTEP, HIGH);
    delayMicroseconds(400);
    digitalWrite(motorPin_rotSTEP, LOW);
    delayMicroseconds(400);
  }

}
////////////////////////////////////////////////////////////////////////////////////

void step_rotCCW(int _noOfSteps) {

  for (int steps = 0; steps < _noOfSteps; steps ++) {
    digitalWrite(motorPin_rotDIR, HIGH);
    digitalWrite(motorPin_rotSTEP, HIGH);
    delayMicroseconds(400);
    digitalWrite(motorPin_rotSTEP, LOW);
    delayMicroseconds(400);
  }

}
```

Appendix B: Logbook

The following pages contain scans from the logbook between a period of 30th October 2024 to 9th June 2025 as noted in the below contents table.

30/10/2024.

"CONNECT TEENSY 4.1 MCU TO GARMIN LIDAR-LITE V3HP.

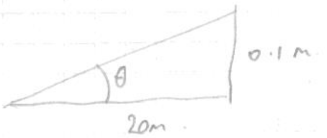


TESTED WITH LIBRARY DEMO CODE - ALL GOOD.

↳ copy on HJWWALTERS.COM/GARMIN

11/11/2024 CALCULATING ROTATIONAL TOLERANCES

CUSTOMER STATES ± 100 mm OVER 20 m RANGE



$\tan\theta = \frac{0.1}{20}$

$\theta = 0.29°$ ROTATIONAL ACCURACY

AS5600 ROTARY ENCODER RESOLUTION = 12 bit

= 4096 segment

$\frac{360°}{4096} = 0.088°$/segment

THEREFORE ROTARY ENCODER COULD THEORETICALLY OFFER

$20 \tan 0.088° = 0.031$ m

± 31 mm OVER 20 m. RANGE

NEMA17 STEPPER RESOLUTION = 200 steps/Rotation = 1.8°/step

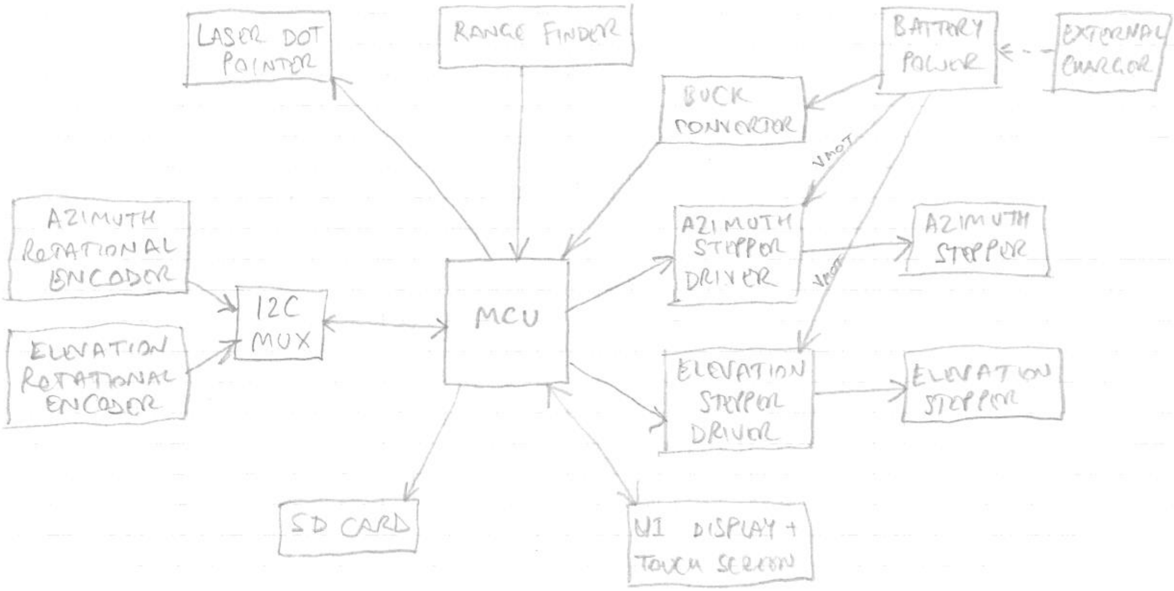
" HALF STEP RESOLUTION = 400 steps/Rotation = 0.9°/step

. . .

16th STEP RESOLUTION = 3200 steps/Rotation = 0.1125°/step

ELEVATION GEARING 60 : 20 = 3 : 1 = 0.0375°/step

11/11/2024 OUTLINE ELECTRICAL SCHEMATIC

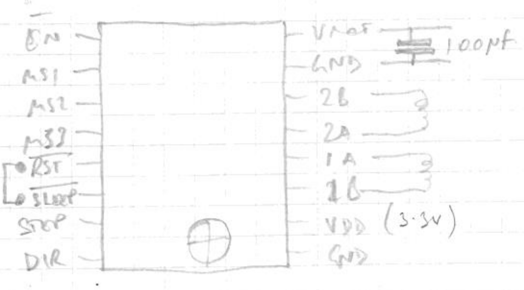


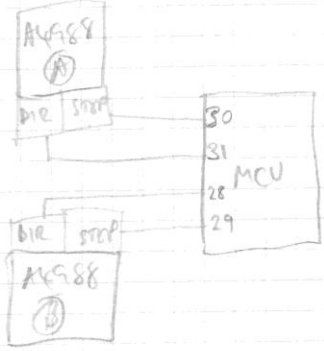
IF A4988 DRIVERS THEN MIN V_{MOT} = 8V.

" DRV8825 " " MIN V_{MOT} = 8.2 V

3S LiPo = 11.1 V
4S LiPo = 14.4 V

14/11/2024 - TEST TEENSY 4.1 MCU WITH 2no A4988 STEPPER MOTORS





TEST OF NEW LASER POINTER

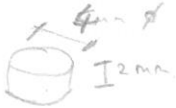
VOLTAGE = 3.3 V. (SET)

CURRENT = 13.4 mA. (MEASURED)

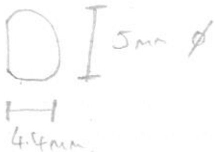
VOLTAGE	CURRENT (mA)	ELECTRICAL POWER
1.7	0.4	
2.0	7.5	
2.1	8.5	
2.2	11.3	
2.3	16.1	
2.4	16.9	
2.5	16.8	
2.6	16.7	
2.7	16.2	
2.8	14.1	
2.9	14.0	
3.0	13.7	
3.3	13.4	0.044 W.
3.6	13.3	
3.9	13.3	
4.2	13.3	
4.5	13.3	
~~4.8~~		
5.0	13.4	

16/11/2024 MAKING AS5600 MOUNTS FOR NEMA 17 STEPPER MOTORS

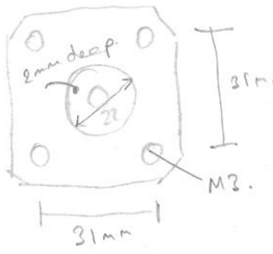
magnet dims



Shaft dims

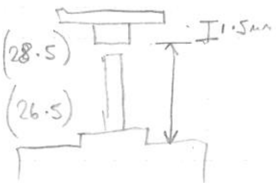


NEMA 17

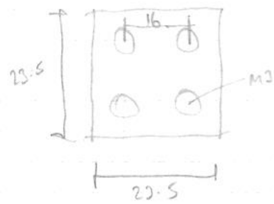


TRONXY HEIGHT = 27mm (28.5)

MYBOTONLINE HEIGHT = 25mm (26.5)



AS5600

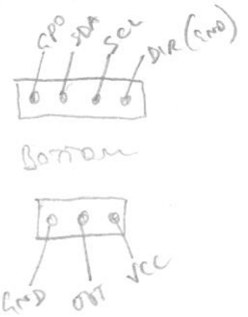


19.5

7 /2 = 3.5

12.5
9.5
16.0

17/11/2024 USING AS5600 ROTARY SENSOR WITH TEENSY MCU.



AS5600	TEENSY 4.1
GPO	- NC -
SDA	18.
SCL	19
DIR.	GND.
GND	GND
OUT	- NC -
VCC	3V3.

CONNECTION OF 2x AS5600 VIA TCA9548 MUX.

TO DO: RUN TEST @ 1/16th. MICROSTEPPING

MICROSTEP PIN = 32

ENCODER RESOLUTION = 2^{12} BIT = 4096 segments per rotation

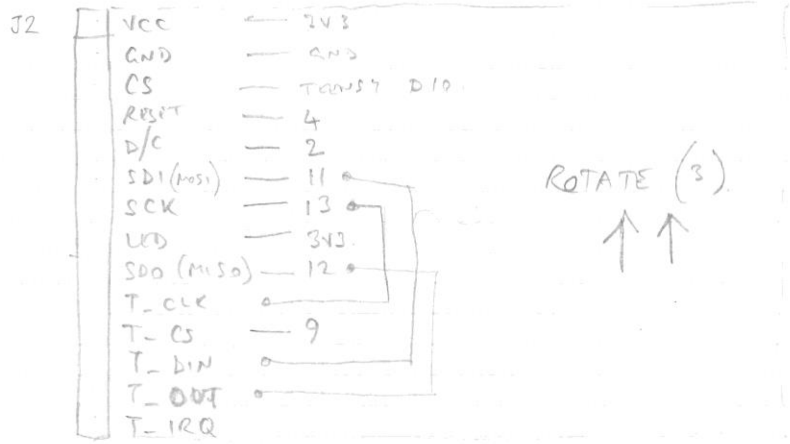
STEPPER RESOLUTION 200 x 16 = 3200 " " "

RATIO $\frac{4096}{3200} = 1.28$

MUX NO.

MY ROT =	29 STEPB	28 DIRB.	MUX_1	CW/CCW
TRONXY :	30 STEPA	31 DIRA.	MUX_0	UP/DOWN

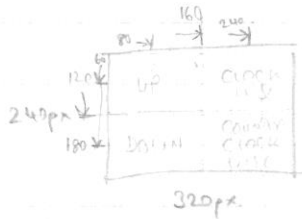
25/11/2024 USING ILI9341 TFT DISPLAY AND XPT2046 TOUCHSCREEN WITH TEENSY 4.1 MCU.



ROTATE (3)

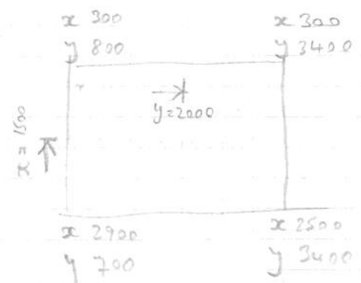
↑↑

CONTROLLING MOTORS WITH TOUCHSCREEN DISPLAY

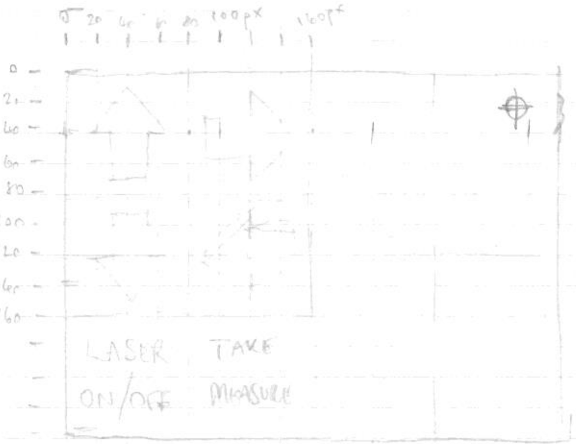


RAW TOUCH VALUES

BUTTON	X	Y.
UP	400 – 1200	800 – 2000
DOWN	1500 – 2400	900 – 1800
CW		
CCW		

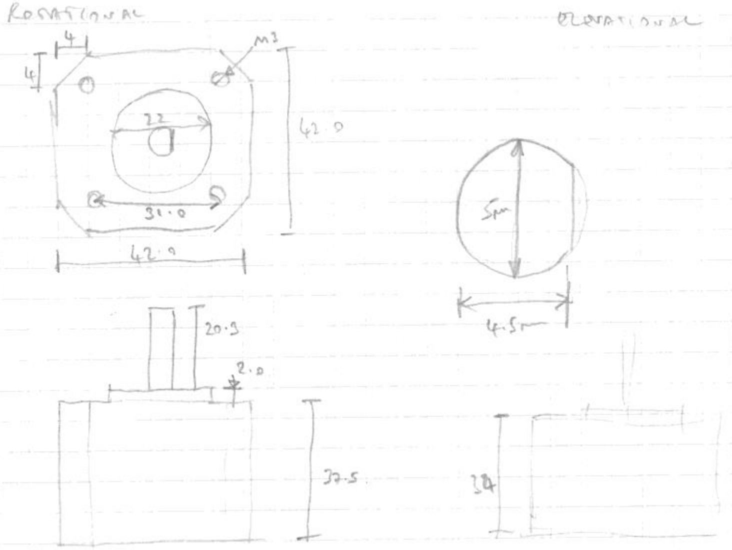



```
if (y > 2000) {
  if (x > 1500) {
    // CCW
  } else {
    // CW
  }
}
if (x > 1500) {
  // DOWN
} else {
  // UP
}
```

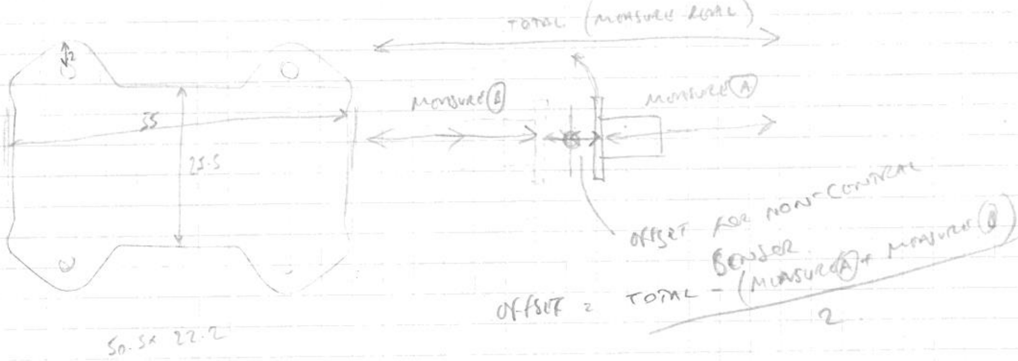


	X	Y
UP	700	900
DOWN	1700	900
L	1700	1700
R	700	1700

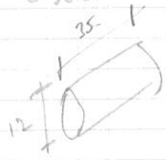
2/12/2024 - 3D models for stepper motors + laser to make test rig



LIDAR

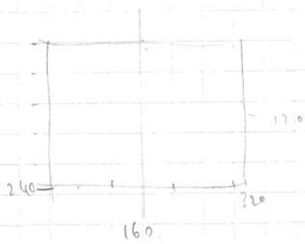


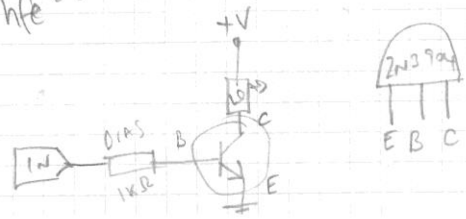
LASER



NPN
2N3904.

hfe = 374.

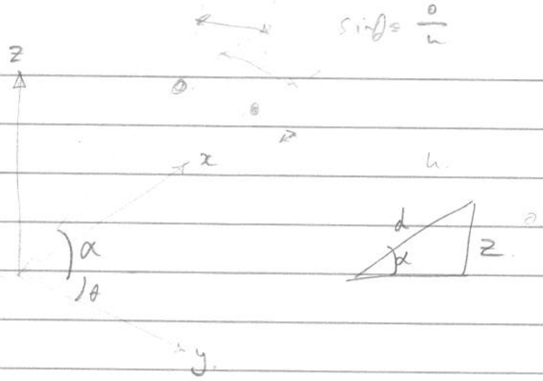


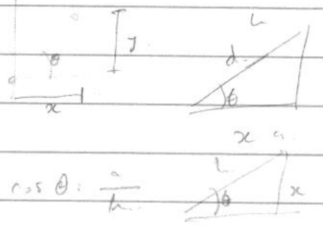


11/12/2024 - LUNCHTIME MATHS

11/12/24.

$\sin\theta = \frac{o}{h}$





$z = d \sin\alpha$

$x = d \cos\theta$

$\cos\theta = \frac{a}{h}$

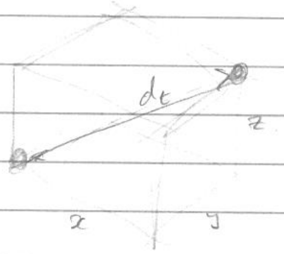
$y = d \sin\theta$

SET DATUM

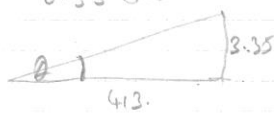
$x_c = |x_1 - x_2|$

absolute value

$d_t = \sqrt{x_c^2 + y_c^2 + z_c^2}$



$$\begin{array}{r} 80.00 \\ -\ 76.65 \\ \hline 3.35 \text{ cm} \end{array} = 4.2\%$$



$\tan\theta = \frac{3.35}{413}$

$\theta = 0.465°$ ERROR.

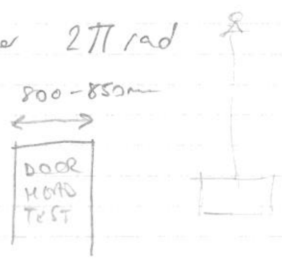
14/12/2024

MOTOR = 200 steps / Rev

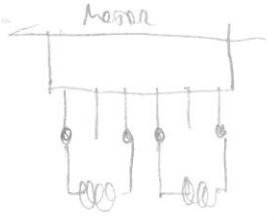
@ 16x microstep = 3200 steps per 2π rad

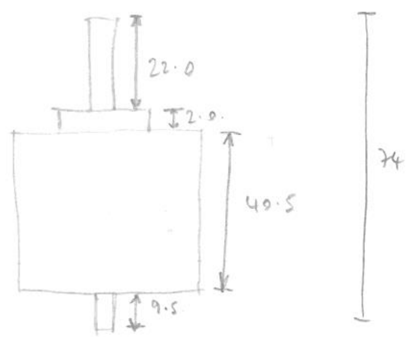
$1\ \mu\text{Step} = 1.963 \times 10^{-3}$ rad/μstep

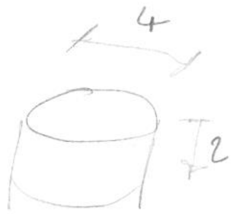
0.00196

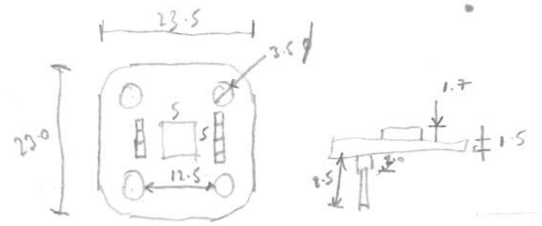


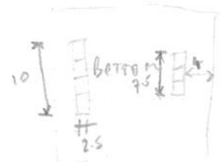
07/01/2025 - 3D MODELLING OF DUAL SHAFT NEMA 17.











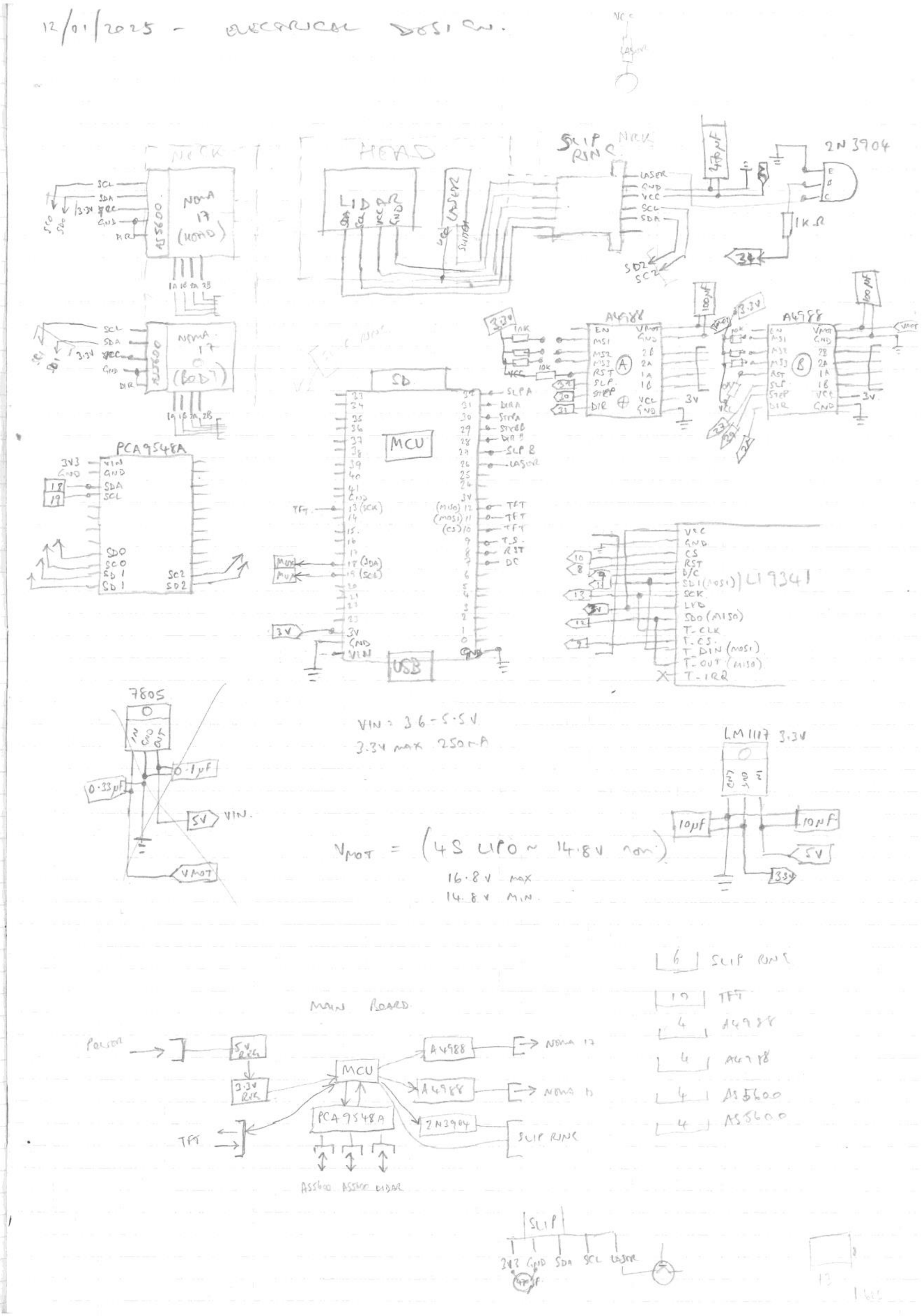
A4988

EN : ENABLE - PULL LOW TO ENABLE (AUTO)

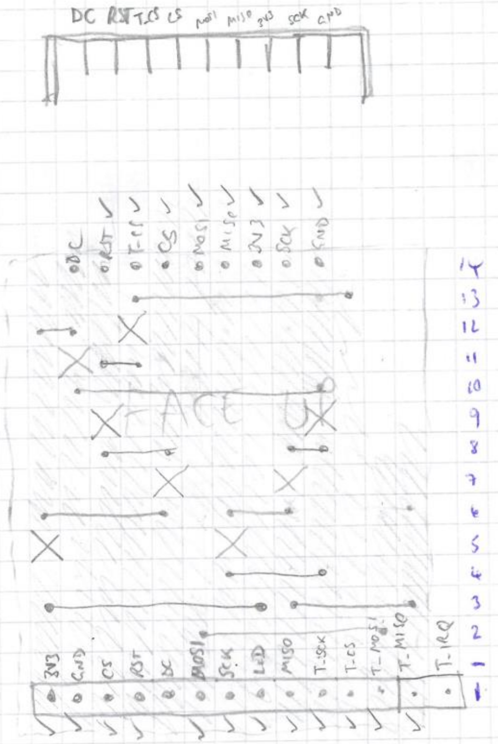
SLP : SLEEP - PULL LOW TO SLEEP (WAIT 1ms AFTER WAKING BEFORE MOVING)

RST : RESET - PULL HIGH TO ENABLE

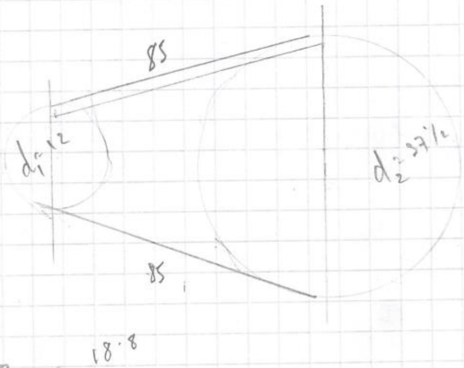
1.5 AMP CURRENT


12/01/2025 - ELECTRICAL DESIGN.
NECK
HEAD
LIDAR
LASER
SLIP RING
2N3904
1kΩ
NEMA 17 (HEAD)
AS5600
NEMA 17 (BODY)
A4988
A4988
SD
MCU
USB
PCA9548A
ILI9341
7805
0.1µF
0.33µF
VIN.
VMOT
VIN = 3.6 - 5.5V
3.3V MAX 250mA
LM1117 3.3V
10pF
10nF
VMOT = (4S LIPO ~ 14.8V nom)
16.8V MAX
14.8V MIN
6 SLIP RING
10 TFT
4 A4988
4 A4988
4 AS5600
4 AS5600
MAIN BOARD
POWER
5V REG
3.3V REG
MCU
A4988
A4988
NEMA 17
PCA9548A
2N3904
SLIP RING
TFT
AS5600
AS5600
LIDAR
SLIP

18/01/2025 - TFT DISPLAY CARRIER BOARD



23/01/2025 - CLOSED LOOP PULLEY FOR HEAD



164

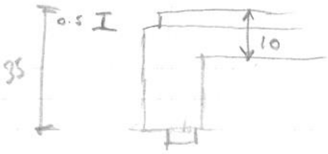
$d_1 = \frac{12\pi}{2} = 18.8$

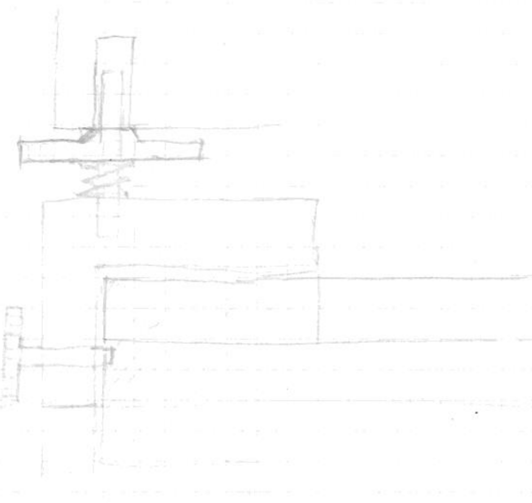
$d_2 = \frac{37\frac{1}{2}\pi}{2} = 58.9$

$+ 2 \times 85$

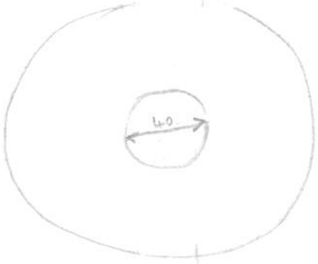
247.

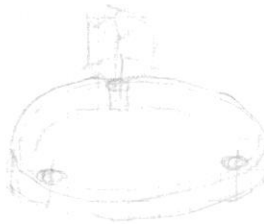
26/01/2025 - Measure TRIPOD

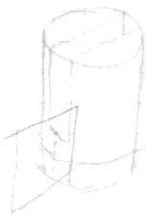


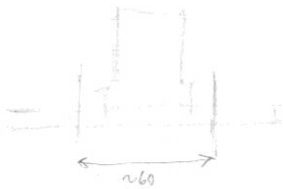


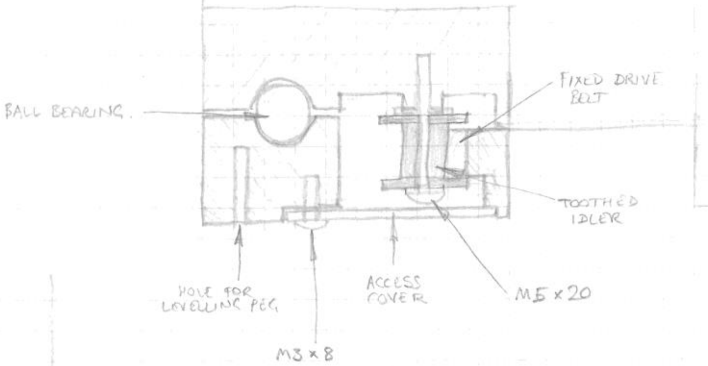
27/01/2025 - INITIAL BASE DESIGNS

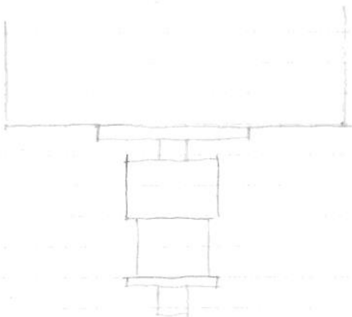


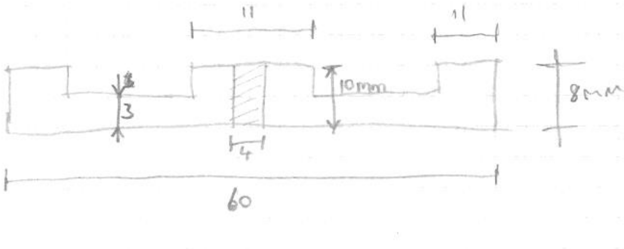


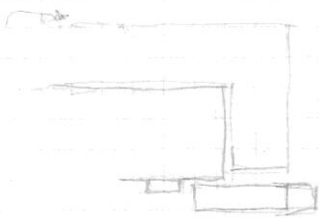




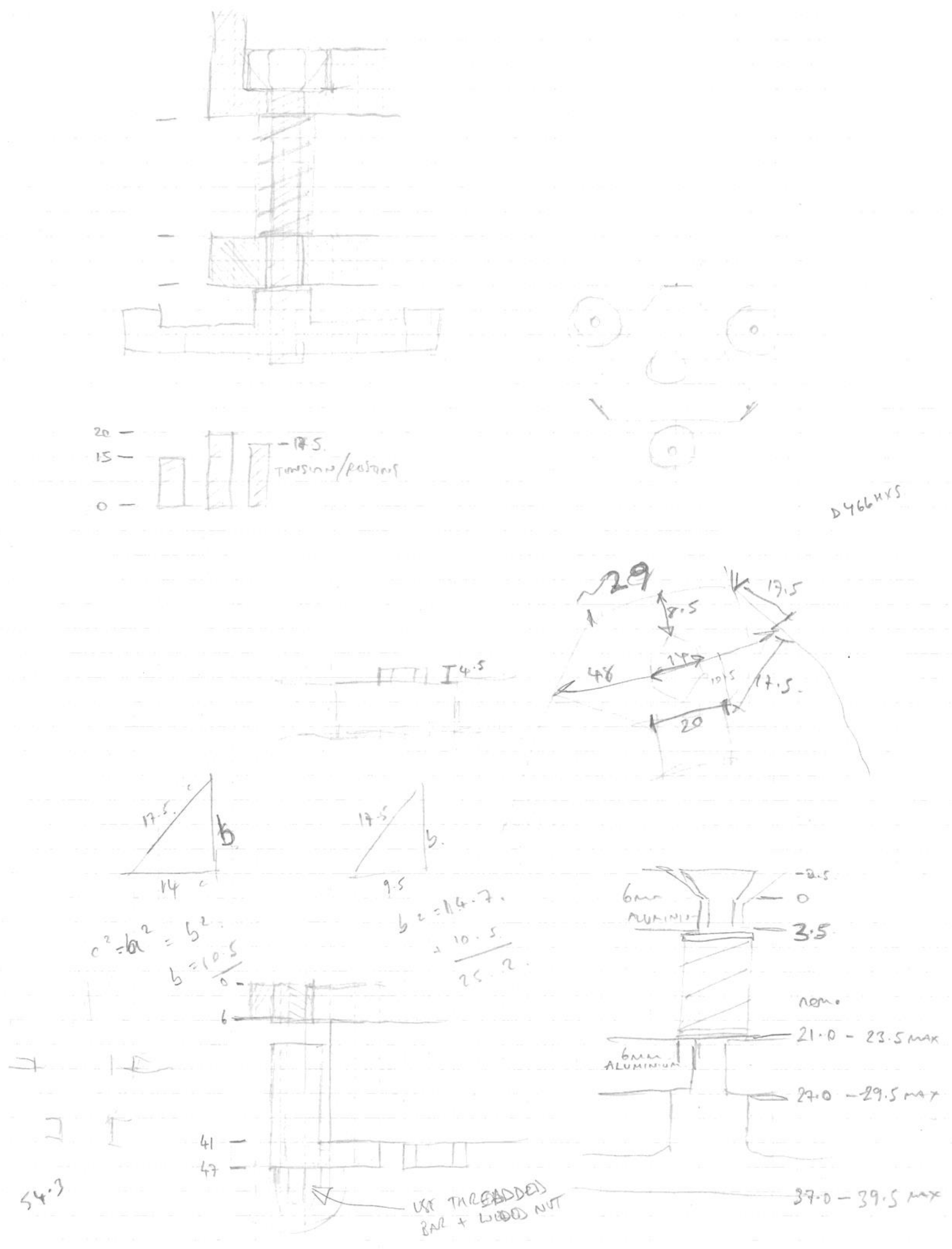




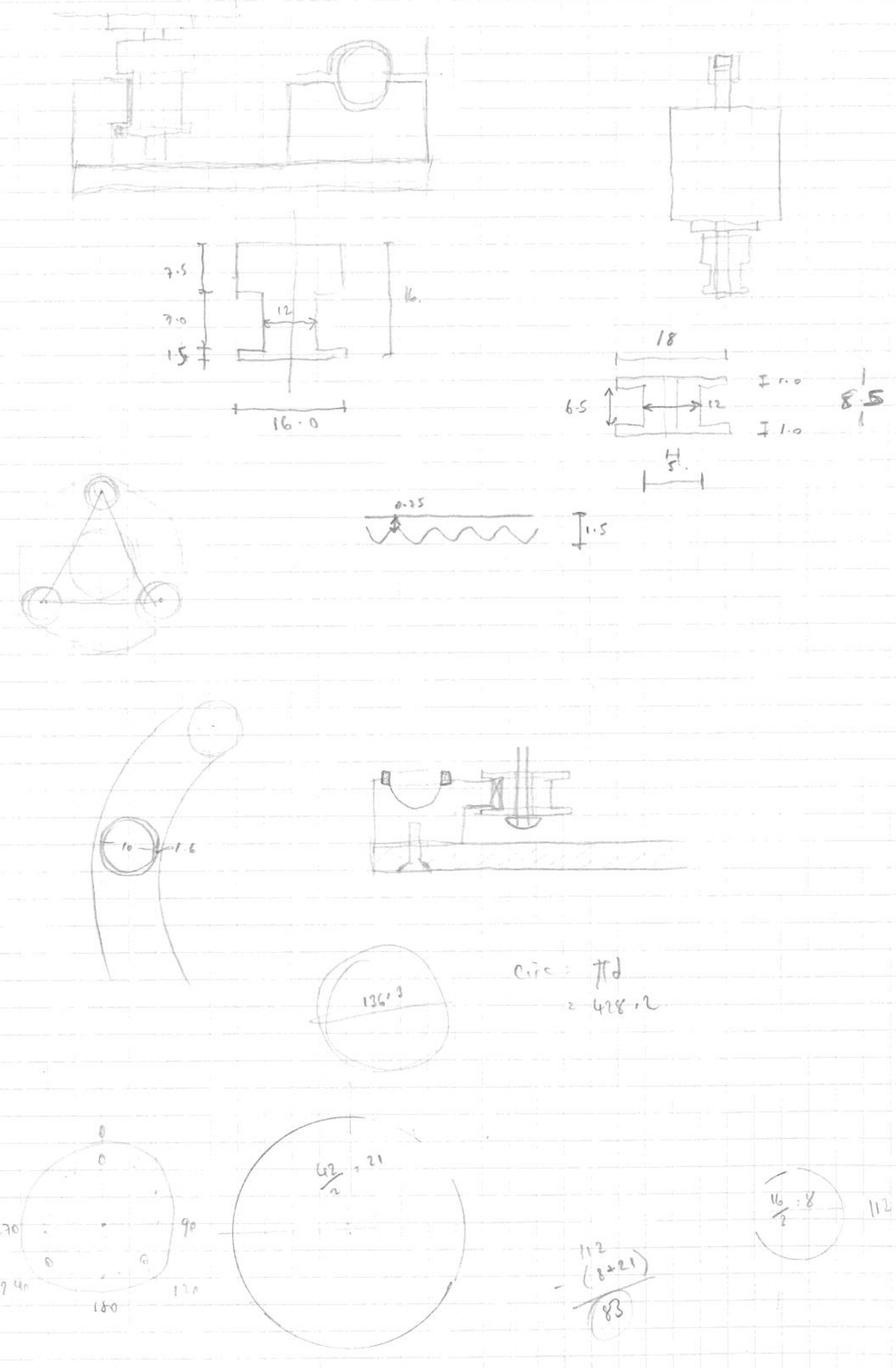




30/01/2025 - CONTINUED BASE DESIGNS.



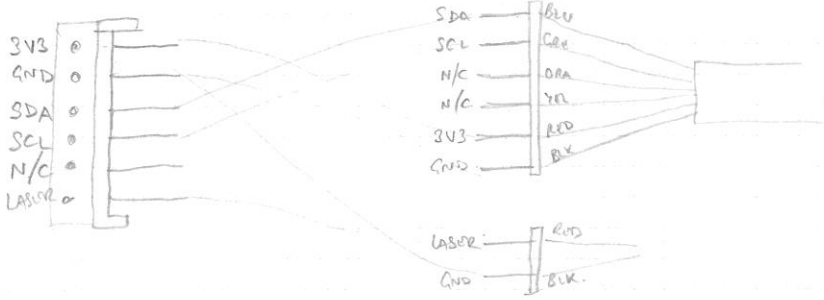
01/02/2025 - Even more base designs



03/02/2025 - formative feedback

- evaluate planning techniques
- critical path analysis.
- compare P.D.S (mechanical winch)

04/02/2025 - electrical sub-system for head



200 × 16 = 3200 steps

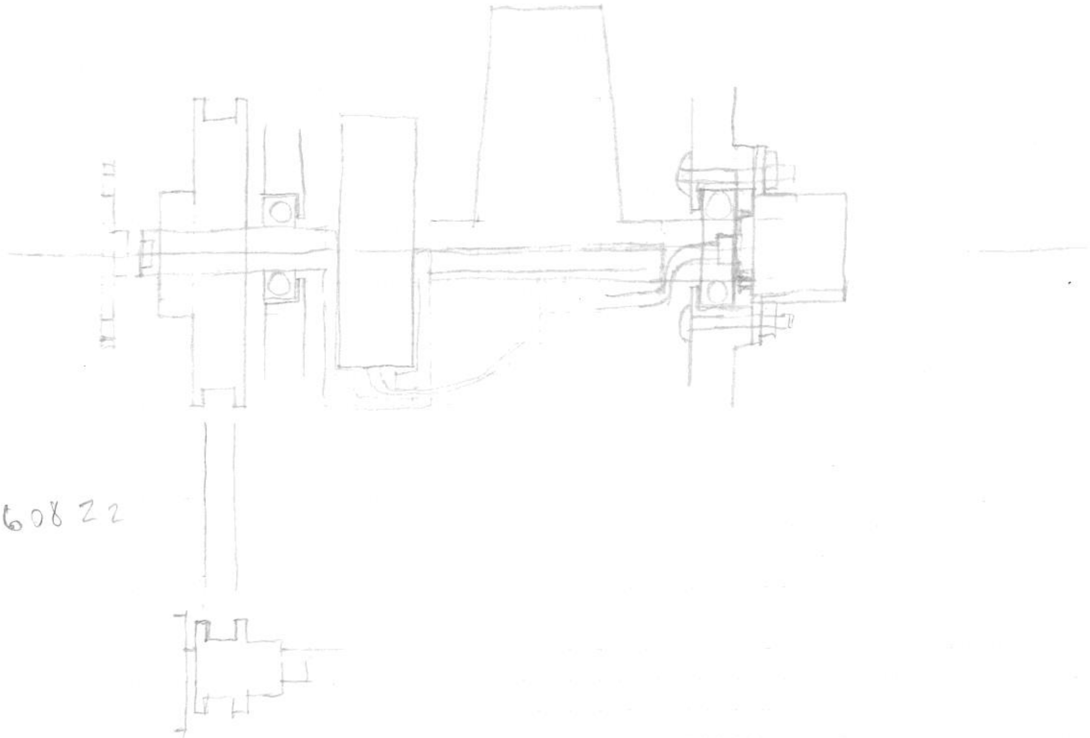
60 : 20 = × 3 ratio

9600 graduations

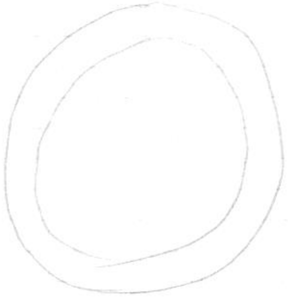
Resolution = 4096

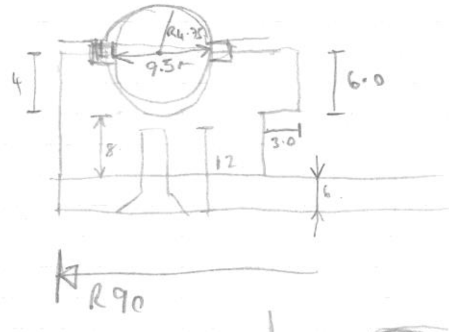
2.34 ×

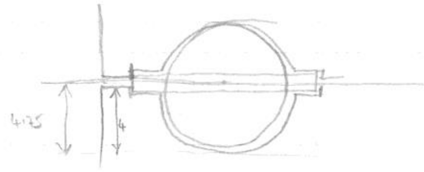
07/02/2025



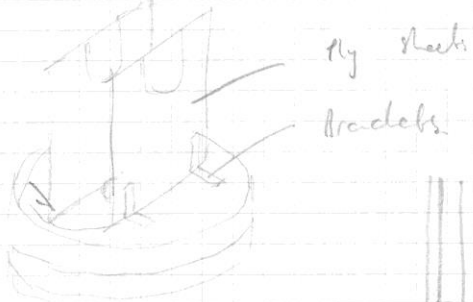
07/03/2025



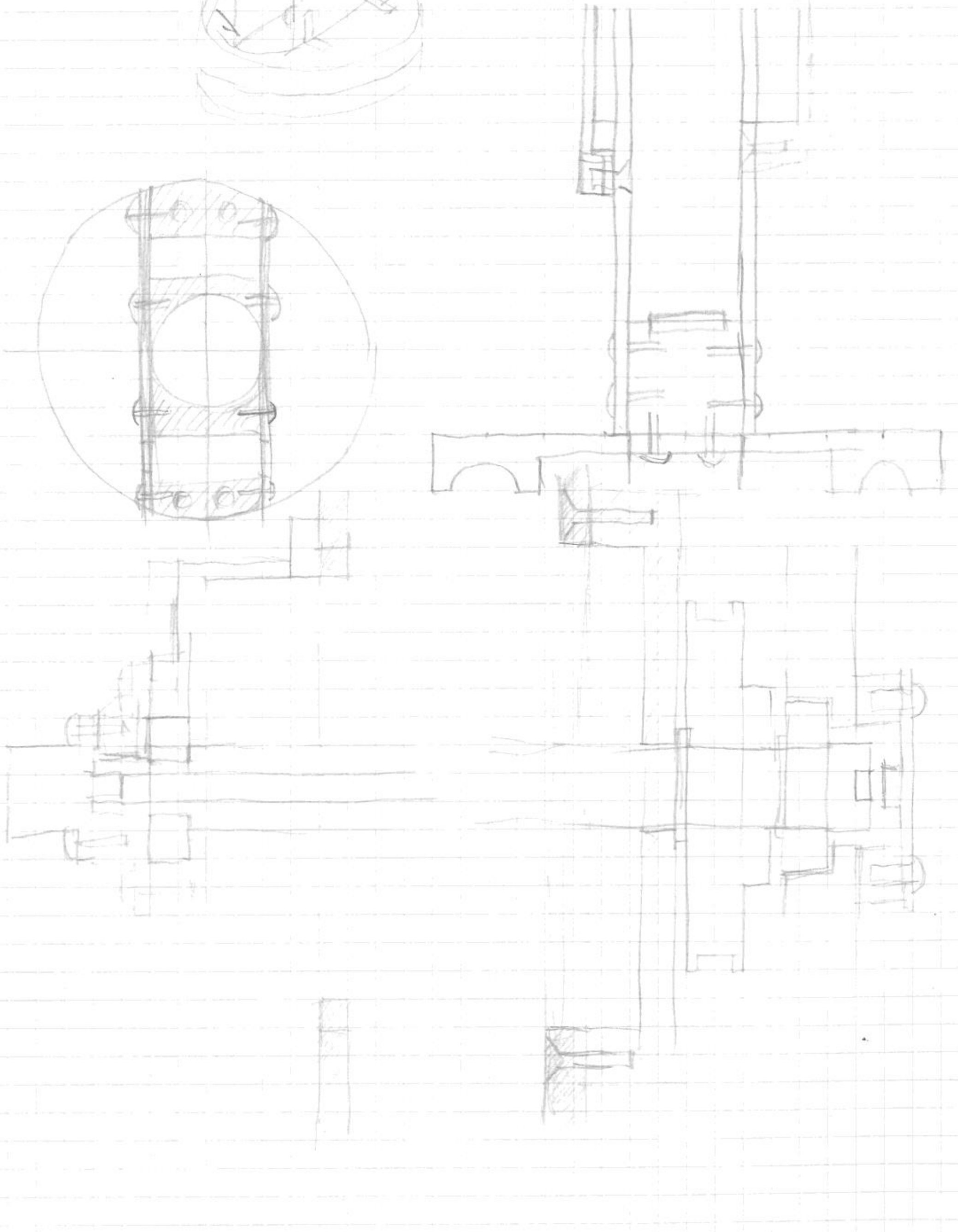




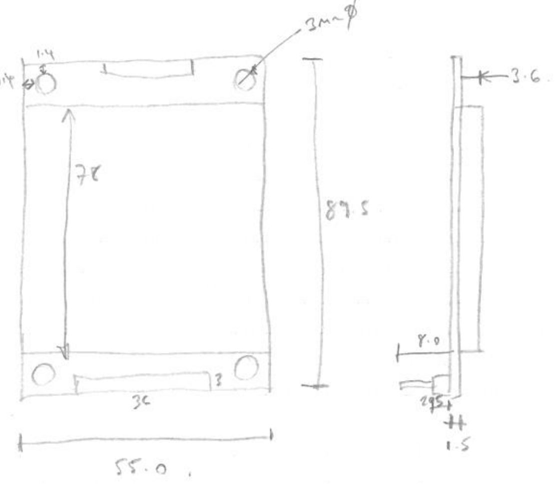
22/03/2025 — DESIGN.

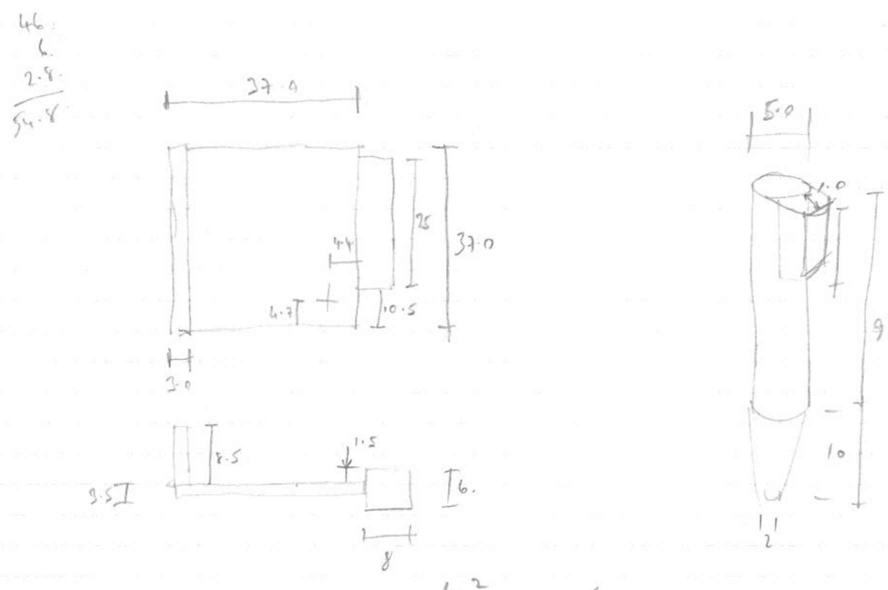


THICKNESS OF PLY = 4.6 mm

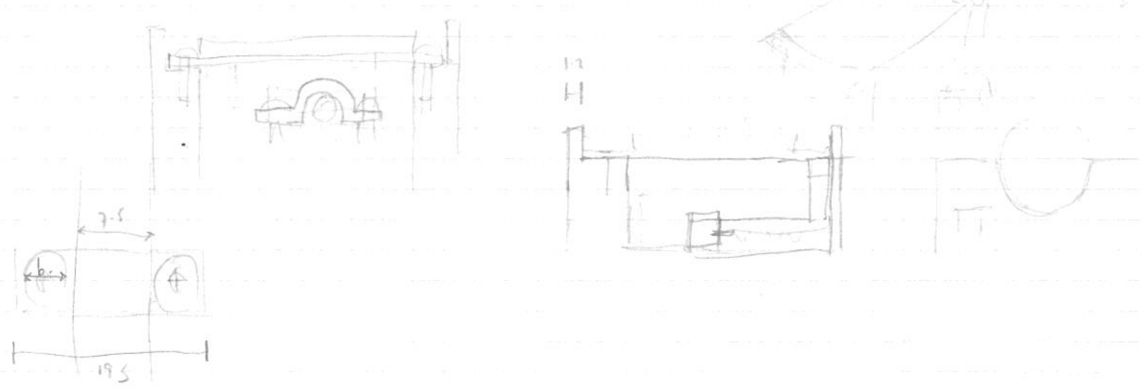


07/04/2025 - CAD TOUCHSCREEN INTERFACE.

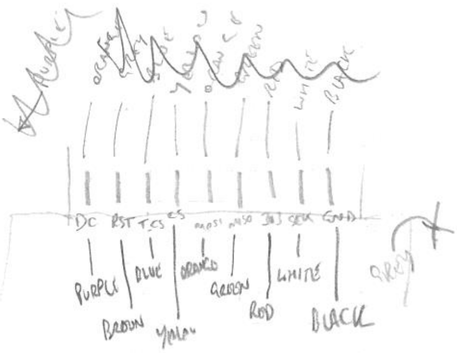


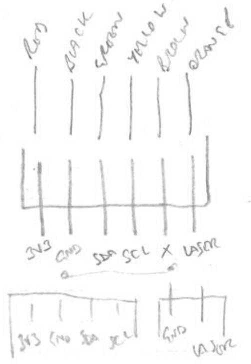


Cable : ~~7.5~~ 6.2 mm ø



12/04/2025 - CONTROLLER WIRING.

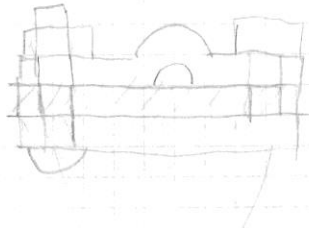


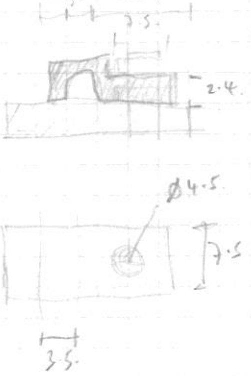


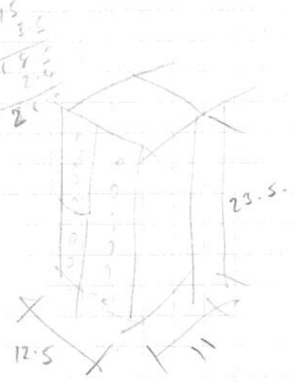
AS5600
SENSORS

5V - RED
GND - BLK
SCL - BLU
SDA - GREEN

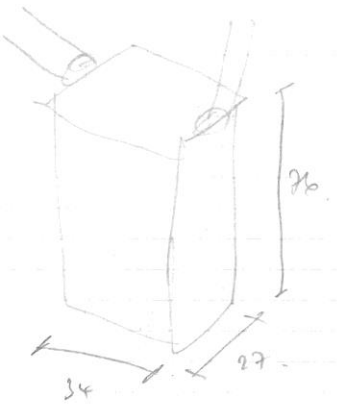
LIDAR
BLACK = GND
RED = VCC
BLU = SDA
GREEN = SCL







18/04/2025. - CAD NEW BATTERIES



20/04/2025

DC
RST
T.CS
CS
MOSI
MISO
3V3
SCK
GND.

PURPLE	DC
BROWN	RST
BLUE	T.CS
YELLOW	CS
ORANGE	MOSI
GREEN	MISO
RED	3V3
WHITE	SCK
BLACK	GND.

21/04/2025 - SUBSYSTEM TEST.

DISPLAY = OK

LASER = FAULT

MUX { LIDAR (MUX CH 1) = OK

AS5600_ROT = (MUX CH 2) = OK

AS5600_ELEV : (MUX CH 3) = OK }

MOTOR - ROT = } OK BUT OVERHEATS!

MOTOR - ELEV. = }

↖ LM1117 3.3V LDO REGULATOR

TOUCH = OK

OVERHEATING OF LM1117 REGULATOR

NO HEAT SINK ≈ 30 s BEFORE SHUT DOWN

WITH HEAT SINK STARTING @ 23.6 °C

33. °C 36 s.

41.6 °C 1m 10 s.

57.3 °C 2:15 s

63.7 °C 2:54s.

66.0 °C 4:00s.

75.0 °C 5:00s.

MAX 91.7 °C @ 5:50 s.

(SMD ~ 93 °C)

RETURNS TO AMBIENT TEMP WITHIN 30 MIN.

12.6 − 3.3 = 9.3 V @ 0.45 A.

P = IV = 0.45 × 9.3 V = 4.2 W.

@ 79 °C/W = 332 °C!

SAY 250 mA THROUGH 5V LDO

200 mA " 3V3 LDO

12.6 − 3.3 = 9.3

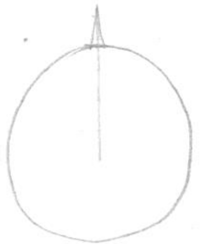
12.6 − 5.0 = 7.6

9.3 × 0.2 = 1.83

7.6 × 0.25 = 1.90

3.73

22/04/2025



360° BASE ROTATION = 2π rad.

ROTATION GEAR RATIO = 214 : 20

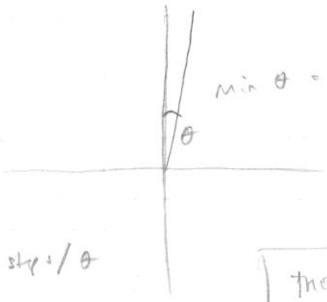
(10.7 : 1)

SENSOR STEPS PER COMPLETE ROTATION

= 4096.0
× 10.7
43827.2 SENSOR STEPS = 2π rads.

∴ 1 sensor step = 1.4336×10^{-4}
= 0.00014336 rad/step

MICROSTEPS 3200
× 10.7
34240 motor steps



Min θ = 0.29°

USE "DOUBLE" DATA TYPE!

$\frac{0.29}{360} \times 34240 = 27.6$ steps/θ

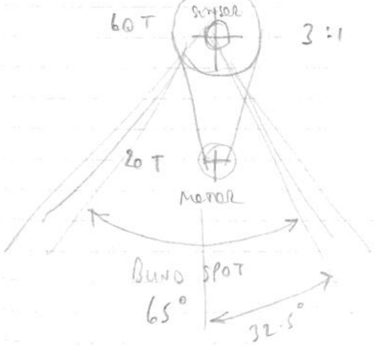
$\frac{0.29}{360}$: 1241.4 seg/360°

32 motor steps = 1070 seg

20 motor steps = 1712 seg

THEORETICAL MAX "RESOLUTION"
4096 ELEVATION
× 43827.2 ROTATION
179.5×10^6 POINTS. ≈ 180 MP

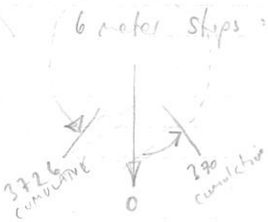
ELEVATION MOTOR



MOTOR STEPS PER REVOLUTION = 3200
× 3
9600 motor steps

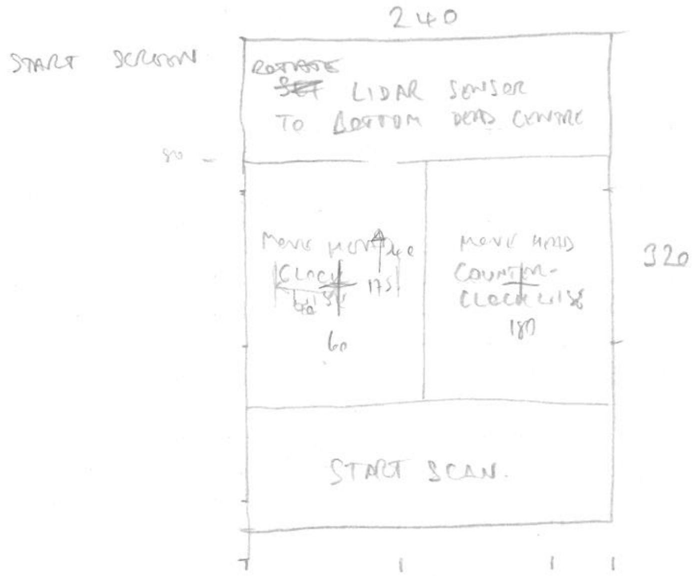
SENSOR STEPS PER REVOLUTION = 4096 sensor steps (2π)
1 step = 1.5340×10^{-3}
= 0.001540 rad/step

6 motor steps : 1600 seg
LESS BLIND SPOT = 1311 seg per elevation sweep



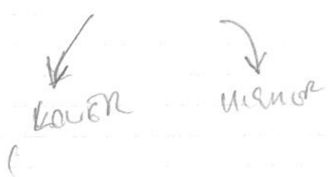
1311 × 1712 = 2244432 points
2.2 MP
15 MINS = 0.0004 s/point ~2500 Hz

23/04/2025 - UI DESIGN



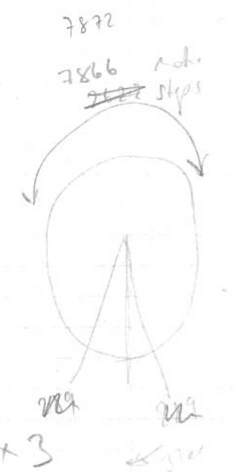
	X	Y
CLOCKWISE BUTTON	~950	~1950
COUNTER CLOCKWISE	~2400	~1950
BEGIN SCAN	~1300	~900

3395



$\frac{32\frac{1}{2}}{360} \times 3200 = 289$ steps motor

365



LOWER

34240 Rot. motor steps } full rot.

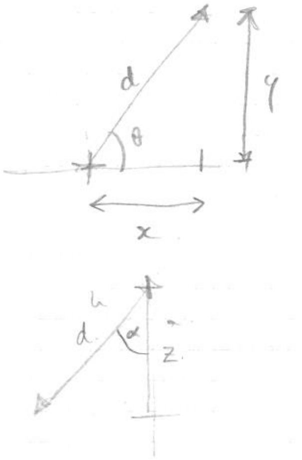
17120 half rot.

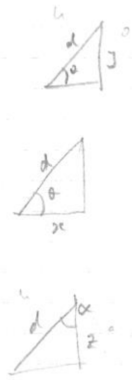
160 × 107 steps = 17120

328 × 24 = 7872

864 + 864 + 7872 = 9600 = 867 × 3

26/04/2025.





$\cos\theta = \frac{y}{d}$

$d\cos\theta = y$ ROT

$\sin\theta = \frac{x}{d}$

$d\sin\theta = x$ ROT

$\cos\alpha = \frac{Z}{d}$

$d\cos\alpha = Z$ ELEV

RAD PER ROT SENSOR = 0.0001434 RAD / SENSOR SEGMENT

2π ↑ ↓ 10.7×2^{12}

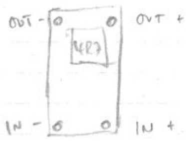
43827.2

RAD PER ELEV SENSOR = 0.001534 RAD / SENSOR SEGMENT

2π ↑ ↓ 4096

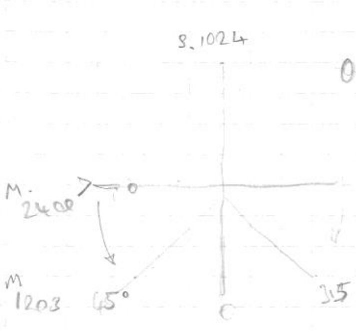
BUCK CONVERTER CONVERSION TO LM1117 PINOUT.

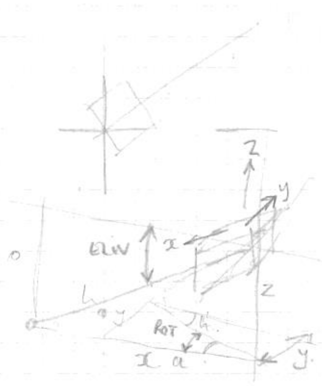
LM1117. GND 3V3 VIN



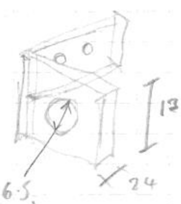
RED = VIN
Yellow = 3V3
BLACK = GND

768168 ms
768863 ms





$\sin\theta = \frac{OPP}{HYP}$



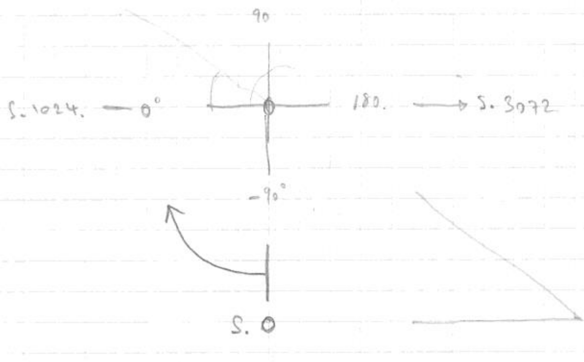
$y = d\sin(ROT)$

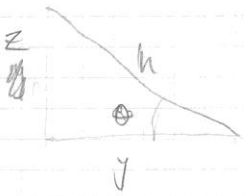
$x = d\cos(ROT)$

$z = d\sin(ELEV)$

17.3.

30/04/2025 - CALIBRATION

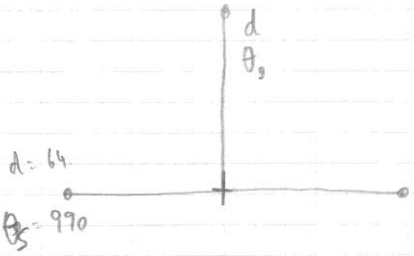


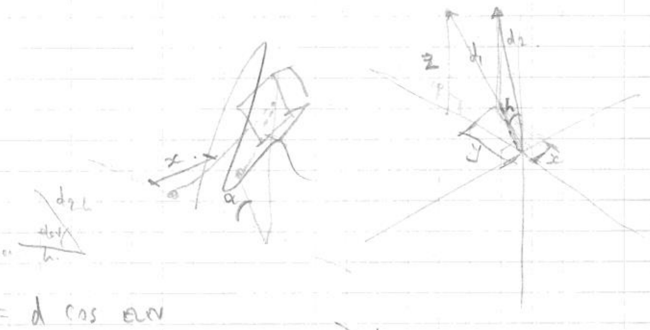


$z = h \sin \theta$

$y = h \cos \theta$

	$\sin \theta$	$\cos \theta$
If $\theta = 45°$	0.707	0.707
AND IF $\theta = 45 + 360°$	0.707	0.707

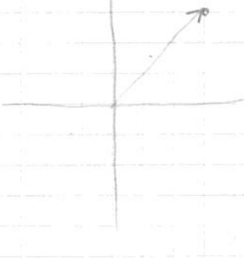




$h = d \cos ELV$

$y = h \cos ROT$

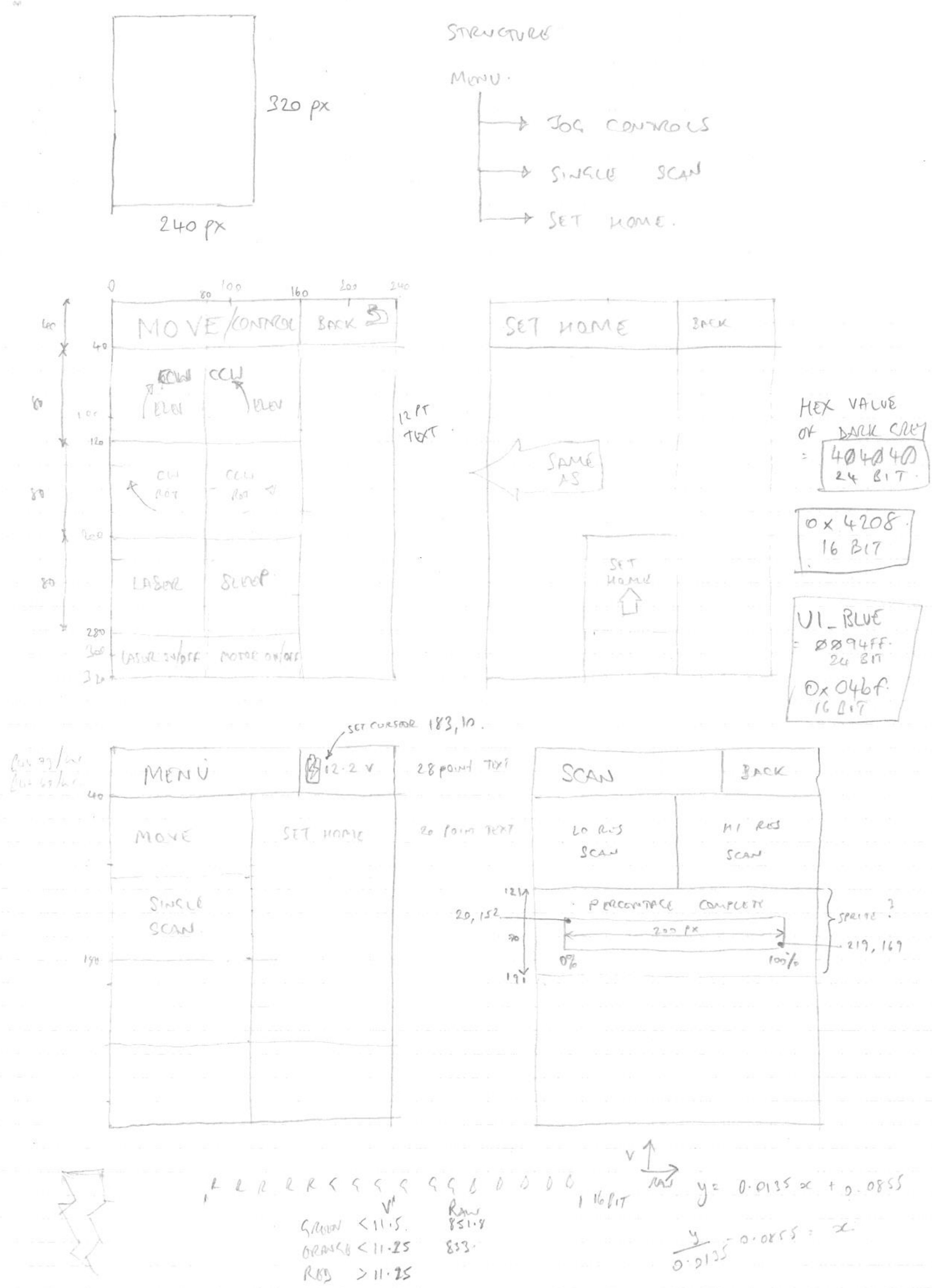
$x = h \sin ROT$



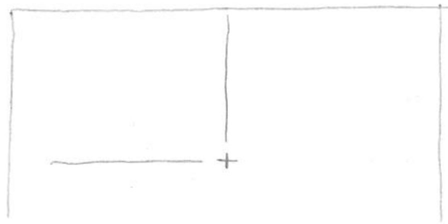
COMPUTE NORMALS → NUM. Neighbour (BIGGER = BETTER) 20 = good (APPLY MULTIPLE TIMES?)
↓
BALL PIVOTING ALGORITHM → CLUSTER RAD = 10%
↓
MIDPOINT SUBDIVISION

576 000
17 120
593 120

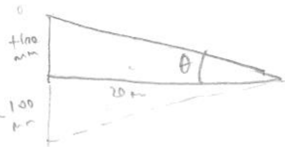
18/04/2025. - INTERFACE DESIGN



22/05/2025 – MATHS ?



DYNAMIC ANGLE ADJUSTMENT
BASED ON DISTANCE ?

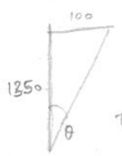


$\tan\theta = \frac{100}{20000}$ $\therefore \theta = 0.286°$

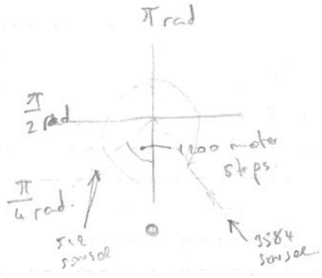
$2\theta = 0.57°$

$\frac{270°}{0.57°}$ = 473 points max

HD = 160 × 300
48000.

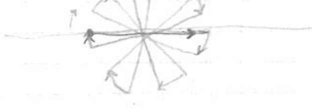


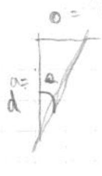
$\tan\theta = \frac{100}{1350} = 4.23$



100 segments
= 1.8 deg
= 171.2 motor steps

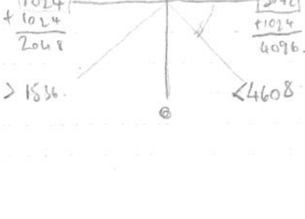
50 × 2 segments





$\theta = \text{atan}\left(\frac{10}{d}\right)$

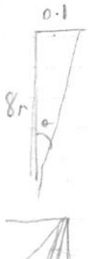
s	2s+1	2s+2
0	1	2
1	3	4
2	5	6
49	99	100



$2\pi = (3 \times 3200)$ motor steps

0.0006545 rad/steps

1527.9 steps per rad

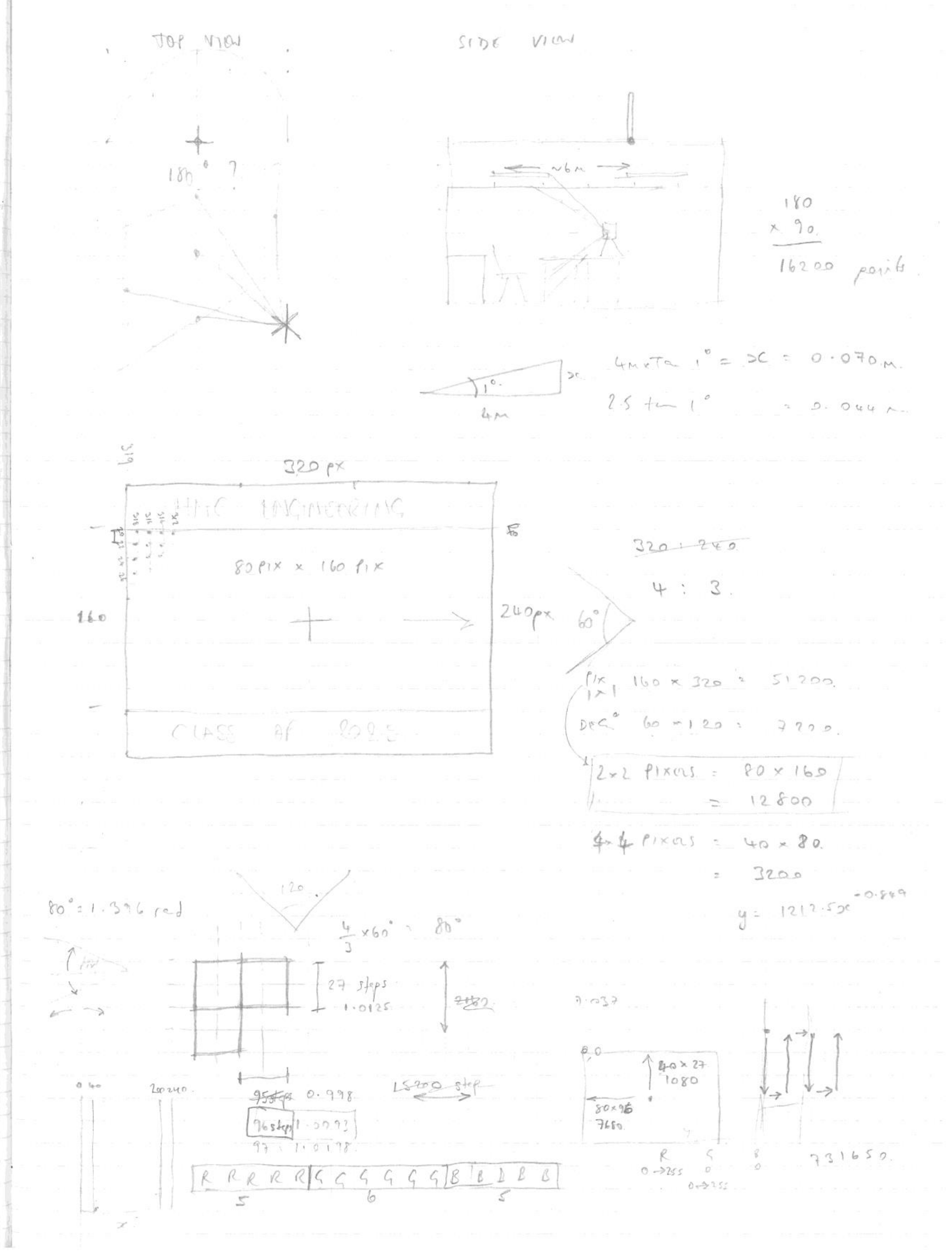


= 0.716°

~ 377 points per.

5:54

24/05/2025. – "photo mode"



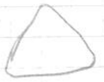
26/05/2025 - PRESENTATION NOTES

ASSEMBLY SUN 20/04.

DISPLAY MOUNT THUR 10/04.

CHECK QUALS -

ENABLE MOTORS.


REDUCE
REUSE
RECYCLE

SAFETY @ START

BETTER PHOTO

ANNOTATE MEASUREMENTS

STITCH SCANS → MORE FUTURE

Lo	11449	in	850 s	14.2 min	13.5 pps.
Lo	12272	in	860 s.	14.3 min.	14.3 pps
Hi	21592	in	1027 s.	17.1 min.	21.0 pps

$y = 4.1767x - 188835.$

$\frac{y + 188835.}{4.1767} = x$

$\text{if } y = \frac{1000000 + 188835}{4.1767} = 284635.$

20/04/2679.

687K

09/06/2025 - FINAL MEASURE

WEIGHT INC. BUCKET = 2.8 kg

SIZE
H 350mm inc cable
W 350 mm } IN BUCKET
D 330 mm

H 200 mm inc cable
W 180 mm } SCANNER ONLY
L 180 mm

HI RES = 14424 pts
832 s.

LO RES = ~~21664.~~ ~~28 856.~~
~~761 s.~~ ~~759.~~

7367
759 s